CHAPTER IV

STUDY OF ANNIHILATION EVENTS.

4.1 INTRODUCTION.

According to Dirac, a direct encounter between a particle and its antiparticle commonly leads to their mutual annihilation. The very existence of antiprotons was finally confirmed when an antiproton got annihilated with a proton in photonuclear emulsion with the release of visible energy greater than the kinetic energy of the particle. Since then, a lot of experiments have been carried out in the hydrogen bubble chambers for the study of antiproton-proton (\(\bar{p}p\)) annihilation characteristics. In a few experiments deuteron targets have been used for studying antiproton-neutron (\(\bar{p}n\)) annihilation characteristics. The importance of \(\bar{p}p\) annihilation lies in the fact that a study of this process may lead to an understanding of the pionization process in PP interactions at high energies. This is because, in the annihilation, the amount of energy available for pionization process is large - a condition which is obtained only for very high incident momentum in the PP interaction. The study of \(\bar{p}n\) annihilation cross-sections are necessary to determine the isotopic spin dependence of antiproton - nucleon annihilation, since annihilations on protons involve the isotopic
spin channels of $T = 0$ and $T = 1$, whereas those on neutrons involve only $T = 1$ channel. It is observed experimentally that the annihilation proceeds equally through the two channels when the it takes place at rest.\textsuperscript{9} But in the range of 1.33 to 5.5 Gev/c incident momenta, Camerini et al.\textsuperscript{111} observed that the annihilation cross-section strongly depends upon isotopic spin. At present $\bar{P}P$ and $\bar{P}N$ total cross-sections are available upto 50 Gev/c incident momentum.\textsuperscript{114} But $\bar{P}P$ and $\bar{P}N$ annihilation cross-sections have been obtained only upto 7 Gev/c\textsuperscript{115} and 5.5 Gev/c\textsuperscript{111} respectively, beyond which annihilation reactions cannot be properly separated from the non-annihilation reactions.

Partial cross-section measurements in the annihilation and non-annihilation channels (comprising of charge-exchange and reemergence of antiprotons) at different incident momenta revealed that the non-annihilation channel competes with annihilation as the incident momentum is rising end, at 5.7 Gev/c, they are nearly equal.

The probable reactions of antiprotons in the elastic, annihilation and non-annihilation channels may be summarised in the following reactions:

(1) Elastic scattering -

\[
\begin{align*}
\bar{P} + P & \rightarrow \bar{P} + P \\
\bar{P} + N & \rightarrow \bar{P} + N \\
\bar{P} + P & \rightarrow \bar{N} + N \quad \text{charge-exchange.}
\end{align*}
\]
(2) Inelastic reactions -
\[
\begin{align*}
\bar{P} + P &\rightarrow \bar{P} + P + \pi^0 \quad \text{reemergence of } \bar{P}. \\
&\rightarrow \bar{P} + N + \pi^+ \quad \text{do} \\
&\rightarrow \bar{N} + P + \pi^- \quad \text{charge exchange.} \\
\bar{P} + N &\rightarrow \bar{P} + N + \pi^0 \quad \text{reemergence.} \\
&\rightarrow \bar{N} + N + \pi^- \quad \text{charge exchange.}
\end{align*}
\]

(3) Annihilation reactions -
\[
\begin{align*}
\bar{P} + P &\rightarrow \pi^+ + \pi^- \quad \text{pion production.} \\
&\rightarrow 2\pi^0 \quad \text{do} \\
\bar{P} + N &\rightarrow \pi^0 + \pi^- \quad \text{do} \\
\bar{P} + P &\rightarrow K^+ + K^- \quad \text{strange particle production.} \\
&\rightarrow \Lambda^0 + \bar{\Lambda}^0 \quad \text{do} \\
&\rightarrow K^0 + K^- \quad \text{do}
\end{align*}
\]

The informations gathered from hydrogen bubble chamber experiments reveal that annihilation events are characterized by low impact parameter and more energy is available for particle creation in these events than in those due to non-annihilation. An annihilation reaction proceeds mainly through the formation of meson resonances. Mostly $\rho$ and $\omega$ resonances are produced, the former moving preferentially in the forward direction and the latter in the backward direction in the centre of mass system. These resonances decay in 2, 3 or more pions and more rarely in $\bar{K}K$ pairs. Hyperons are also created during annihilation, the cross-section for which
increases with incident momenta. The production cross-section of various $\bar{K} + n\pi (n = 0, 1, 2 \ldots)$ final states decreases with increasing incident momenta, and at 5.7 GeV/c, (which is the nearest to our incident momentum) it is $(3.5 \pm 0.3) \text{ mb}$. Hyperon production cross-section at 7 GeV/c incident momentum is reported to be $(1.3 \pm 0.1) \text{ mb}$ by Fisher et al (Data at 5.7 GeV/c is not available).

In the annihilation into pions, the observed average negative pion multiplicity is much larger than those produced in the PP interactions. The multiplicity distributions of the annihilation processes are much narrower than those of non-annihilation ones. The ratio of total pion multiplicity to the charged pion multiplicity, $\frac{N_{\pi^+}}{N_{\pi^0}}$, is 1.8, instead of 1.5 according to charge independence reactions in the strong interactions. In annihilation, as the number of negative pions goes on increasing, the average number of neutral pions goes on diminishing; while in PP interactions this correlation is more or less flat or slightly rising. This difference is attributed to copious production of $\phi$ meson in annihilation channels as compared to PP interactions. Average transverse momentum of pions in annihilation is higher than that in non-annihilation interactions.

To explain all these behaviours of $\bar{p}p$ annihilations, observed in hydrogen bubble chambers, no theoretically suitable model has yet been offered. However, an
attempt was made to explain the annihilation and non-annihilation components via the internal structure of nucleon and antinucleon where the nucleons were assumed to have hard core, and annihilation occurs only when core and anticores meet.

When an antiproton annihilates with a nucleon inside the nucleus, although the basic characteristics of annihilation such as the nature of shower multiplicity distribution, transverse momentum spectrum of pions etc, are similar; some other dissimilarities appear. This is because of secondary interactions and absorption of pions within the nucleus. Systematic studies of antiproton heavy-nucleus interactions and subsequent annihilation of the antiprotons were studied by some groups of workers immediately after it was discovered. The incident momenta of the antiprotons were low and were below 700 Mev/c in all these experiments. Agnew et al had studied the annihilation of antiprotons in the oxygen, copper, silver and lead nuclei. They observed increase of annihilation cross-section with the mass number of the target nuclei for nearly similar incident momentum of the antiproton. Apostolakis et al found that for annihilation of antiprotons at rest in the nuclei of nuclear emulsion, annihilation with proton and neutron proceeded equally. According to Aamaladi et al, some pions made secondary interactions within the nucleus and on the average $2.25 \pm 0.20$ number of pions were absorbed
in an emulsion nucleus, when the antiproton interacted in flight.

A study of annihilation of antiprotons with complex nuclei is necessary in order to know how the $\bar{p}p$ annihilation products (specially shower particles) are modified by the nucleons of the nucleus. In our experiment, we have compared the results with that for $\bar{p}p$ annihilation at 5.7 GeV/c\textsuperscript{18} and $\bar{p}$-nucleon\textsuperscript{89} annihilation at 5 GeV/c incident momenta. Secondly it is of interest to note the difference in the behaviour of $\bar{p}$-nucleus and $p$-nucleus interactions. In some cases we have found our result to be somewhat similar in nature to that of $p$-nucleus interaction at 24 GeV/c\textsuperscript{117} (eg. variation of average transverse momentum with the angle of emission).

In this chapter, results on annihilation characteristics of 5 GeV/c antiprotons with heavy emulsion nuclei (ie Ag and Br) have been presented. This particular experiment of ours had been performed to make a systematic study of annihilation at higher incident momentum. We selected only silver and bromine nuclei of the nuclear emulsion because, as it has been already stated, the annihilation cross-section is large for interaction with heavy nuclei.
4.2 EXPERIMENTAL PROCEDURE

(a) Selection of events:

It is difficult in emulsion to separate the annihilation and non-annihilation interactions comprising of charge-exchange and reemergence events, because of the secondary interactions within the nucleus. To separate the reemergence events, one has to examine carefully all the forward going shower particles for their mass and charge which can be done by multiple coulomb scattering (\(p_8\)) and grain density (\(b^*\)) measurements. This is a very tedious task to do for a sample of 1322 stars. Secondly, in a charge-exchange reaction, most of the incident momentum is carried away by the antineutron and the star produced is small. Since the interaction is within the nucleus, it is difficult to determine whether the star was due to annihilation with large number of neutral particles produced or due to a charge-exchange reaction. So we used a method to separate the annihilation events from the sample of 1322 primary stars. For this purpose we calculated the approximate total energy released in each and every primary star, using an equation given by Powell et al., with a slight modification, which is

\[
E (\text{MeV}) = 2.2E_g B_g + E_b(N_b + 4 x 3N_b) + 6(N_b + N_g) + \\
\frac{3}{2} N_g (B_g + 140).
\]
where \( \bar{E}_b \) is the average energy for the black tracks in a star, 

\[ \bar{E}_b \text{ kinetic} \]

\( \bar{E}_g \) is the average energy of the grey tracks in a star,

\[ \bar{E}_g \text{ kinetic} \]

\( \bar{E}_s \) is the average kinetic energy of the shower tracks in a star,

140 Mev = Rest energy of pions. The ratio of charged to neutral pions is assumed to be 2 : 1.

In this equation (4.1) the first term represents the kinetic energy of the grey tracks. The ratio of neutrons to protons among the grey particles is 1.2, which is their relative abundances in the nuclear matter. The second term represents the kinetic energy of the black tracks. For the evaporation process, slow neutrons are much more frequent and neutron to proton ratio is assumed to be nearly 4. In the last stages, as temperature falls from about 4 to 2 Mev, neutron emission becomes more probable and nearly three extra neutrons are commonly emitted. The third term represents the total binding energies of black and grey tracks. We have added the fourth term which takes into account the total energy taken out by shower particles. In chapter III we observed that nearly 76% of the shower particles in our events were pions. So we calculated the approximate total energy in the stars assuming all the showers to be due to pions. Of course due to such assumption, we would get lower estimation of total energy released.
in the stars. We have taken the values of average kinetic energies for black, grey and shower tracks to be 8.7 Mev, 110 Mev and 305 Mev respectively which we obtained by actual measurement as given in Chapter III.

The distribution of total energy released in the stars is shown in Fig. 9. The nature of distribution seems to show that the annihilation and non-annihilation events are not separable from each other. There is no doubt that the stars where the approximate total energy released is greater than the incident energy i.e. 4.2 Gev, are genuine annihilation stars. But there are other annihilation stars with calculated energy release less than 4.2 Gev from where more neutral particles might have been emitted than are accounted for in the equation (4.1). We collected altogether 242 stars with total energy release greater than 4.2 Gev and studied the characteristics of these annihilation stars.

(b) Measurements :-

Out of 242, all the shower tracks escaping from 85 random stars with range >4mm and dip within 10°, were collected for multiple coulomb scattering (pB) and grain density (b*) measurements. We could collect only 50 showers satisfying the above two criteria. 50 grey tracks of range >3mm and dip within 30° in unprocessed emulsion were also recorded for multiple coulomb scattering measurement. The measurements were performed in the Koristka microscope and corrections were made in the same way as described in Chapter II and III. Identification of these showers were made as
Fig-9. Energy distribution in stars.
before (illustrated in Chapter III) and were found that 45 of them were pions and 5 were kaons. The space angles of all the shower tracks escaping from 85 stars were measured and from the space angle distribution of 50 showers, total number of pions and kaons among the total shower tracks were determined. The values obtained were 90% pions and 10% kaons. The fraction of kaons in our sample of annihilation stars is somewhat larger than obtained in other hydrogen bubble chamber experiments.

4.3 EXPERIMENTAL RESULTS

(a) Star characteristics:

The distributions of heavily ionizing ($N_{h_A}$), grey ($N_{g_A}$) and shower ($n_{s_A}$) tracks in the annihilation stars, are shown in Fig.10a, 10b and 10c respectively. The mean values are $\bar{N}_{h_A} = 21.95 \pm 2.7$, $\bar{N}_{g_A} = 6.33 \pm 0.41$ and $\bar{n}_{s_A} = 2.7 \pm 0.17$ respectively. These values are much larger than those observed in the general characteristics of the stars studied in Chapter III. This is not unexpected from the fact that in annihilation whole of the incident energy is available for disintegration of the nucleus. The distribution of shower multiplicities ($n_{s_A}$) for antiproton- nucleon annihilations in emulsion at 5 Gev/c have been shown in the same Fig.10c by dotted lines, where the mean value of shower multiplicity obtained was, $\bar{n}_{s_A} = 4.1 \pm 0.5$. The nature of distributions in both the cases are more or less similar.
Fig-10a. $N_{h_A}$ distribution of $A$-annihilation stars.

Fig-10b. $N_{g_A}$ distribution of $A$-annihilation stars.
Fig-10c. $n_s^A$-distribution of annihilation stars

- 5 GeV/$c$-$\bar{P}$ nucleus collision.
- 5 GeV/$c$-$\bar{P}$ nucleon collision.
In Fig. 11a, 11b and 11c we have plotted the variation of average shower multiplicity, $\bar{n}_A$, with $N_h$, $N_b$ and $N_g$ respectively. In all these cases $\bar{n}_A$ diminishes with them according to the relations:

$$
\bar{n}_A = 7.7 - (0.20 \pm 0.04) N_h
$$

$$
\bar{n}_A = 6.0 - (0.19 \pm 0.04) N_b
$$

$$
\bar{n}_A = 4.8 - (0.39 \pm 0.10) N_g
$$

The numerical values were obtained from the least square fit method. A similar relation between $\bar{n}_A$ and $N_h$ was obtained by Chamberlain et al in the study of annihilation of antiprotons with emulsion nuclei when the incident momentum was less than 700 Mev/c.

According to the experiment of Kamal et al the reemerging antiproton takes away a large fraction of the incident momentum ($\sim 3.5$ Gev/c), and moves in the extreme forward direction. In four pellicles, we selected 46 stars, each having an identified shower particle of protonic mass moving along extreme forward direction within $10^0$ of the primary beam. We assured that these stars were produced due to non-annihilation reactions. Three plots of $\bar{n}_S$ against $N_h$, $N_b$ and $N_g$ were drawn separately for these stars. Although there was large statistical fluctuation, it can be said that $\bar{n}_S$ remained practically constant for different values of $N_h$, $N_b$ and $N_g$. The solid lines obtained by the least square-fit method are shown in Fig 12a, 12b and 12c respectively. Hence we assume that variation of $\bar{n}_S$ with $N_h$, $N_b$, and $N_g$ in the manner we obtained and shown in Fig 11 might be due only to annihi-
Fig. 11a: Variation of average $n_s$ with $N_{h_A}$ (annihilation stars)
Fig. 11b. Variation of average ns with N."
Fig.-11c. Variation of average $\bar{n}_{s_A}$ with $N_{g_A}$
Fig-12a. Variation of average $n_s$ with $N_h$
(non annihilation stars)

Fig-12b. Variation of average $n_s$ with $N_b$
(non annihilation stars)
Fig.-12c. Variation of average $n_s$ with $N_g$

( non annihilation stars)
letion reactions.

(b) **Angular distribution of shower particles**: -

Angular distribution of shower particles in the laboratory system as a function of $\log \cot \theta$, $\theta$ being the laboratory emission angle with respect to the primary direction, is shown in Fig 13. Nearly one fourth of the showers are emitted in the backward direction. Their distribution is also shown in the same figure by dotted lines. Comparing these two angular distributions with that of general characteristics of stars in Chapter IV, it is seen that the angular distributions of the showers in the annihilation events are narrower and more backward peaked. Assuming Gaussian distributions for these angular distributions, forward moving showers are seen to peak around $28.3^\circ$ and backward moving pions around $(90^\circ + 45^\circ = 135^\circ)$ in the laboratory system.

(c) **Momentum distribution of pions and cascade protons**: -

The momentum distribution of pions in the laboratory system is shown in Fig 14a. The nature of distribution is very nearly similar to that obtained by Bhowmik et al in the study of $\bar{\Phi}$-nucleon annihilation in emulsion at 5 Gev/c. The mean value obtained by us is $449 \pm 33.5$ Mev/c in the laboratory system and the mean value obtained by Bhowmik et al is $336\pm 41$ Mev/c in the centre of mass system. The momentum distribution of grey tracks, which are protons, is shown in Fig 14b. Mean momentum is found to be $229\pm 46$ Mev/c.
Fig 13. Angular distribution of shower particles

- Forward going pions (164 events)
- Backward going pions (41 events)

Log Cot θ lab

40 30 20 10

No of shower tracks

45° 28.3°
Fig. 14a. Momentum distribution of pions

Fig. 14b. Momentum distribution of grey tracks.
(d) **Transverse momentum distribution of pions:**

The transverse momentum distribution of pions is shown in Fig. 15. The mean value was found to be $p_t = 223 \pm 16.6$. The values obtained in the $\bar{P}$-nucleon, $P$ - nucleon and $\pi$ - nucleon interactions at similar incident momentum and for $P$-nucleus interaction at 24Gev/c are given in the Table 1.

**Table 1**

<table>
<thead>
<tr>
<th>Incident beam</th>
<th>Type of interaction</th>
<th>Average System</th>
<th>$p_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 Gev/c $\bar{P}$ - nucleon</td>
<td>236±11</td>
<td>$6.\pi$</td>
<td>89</td>
</tr>
<tr>
<td>6.2 Gev $P$ - nucleon</td>
<td>225±33</td>
<td>lab</td>
<td>88</td>
</tr>
<tr>
<td>4.4 Gev $\pi$ - nucleon</td>
<td>300±23</td>
<td>lab</td>
<td>118</td>
</tr>
<tr>
<td>24 Gev/c $P$ - nucleus</td>
<td>223±16</td>
<td>lab</td>
<td>117</td>
</tr>
<tr>
<td>5 Gev/c $\bar{P}$ - nucleus</td>
<td>223±16.6</td>
<td>lab</td>
<td>Present Expt.</td>
</tr>
</tbody>
</table>

Average transverse momentum, $p_t$, is nearly equal within statistical error for all the interactions except $\pi$-nucleon interactions at 4.4 Gev. Also it has been observed that $p_t$ distributions in $P$-nucleon and $P$-nucleus collisions can be best represented by a linear exponential curve while that in the $\bar{P}$-nucleon and $\bar{P}$-nucleus interactions can be best fitted with a Boltzmann distribution curve.

In Fig. 16 we have plotted $p_t$ distribution of pions against laboratory angle of emission. Somewhat similar
Fig. 15. Transverse momentum distribution of pions

- $p$-nucleus at 5 GeV/c
- $p$-nucleus at 24 GeV/c
- $p$-nucleon at 6.2 GeV/c

Fitted distribution, $f(x)dx = \frac{x}{b^2}e^{-\frac{x^2}{2b^2}}dx$ where $b = 112$ MeV/c. (Ref. 36)

Fitted distribution, $Ndx = 2.667 \times 10^{-4} e^{-12.194x^2}dx$.
dependence of $\vec{p}_t$ for pions was observed in the $\pi$-nucleon, nucleon-nucleon and nucleon-nucleus collisions by Malhotra\textsuperscript{118}, Ciurlo et al\textsuperscript{119}, Kohli\textsuperscript{120}, Kamal et al\textsuperscript{121} and Ahmed et al\textsuperscript{117}. In our observation we found that $\vec{p}_t$ was increasing with angle of emission up to 40°, kept nearly constant up to 70° and then it diminished.

We also studied the variation of $\vec{p}_t$ of pions with $n_s$ for different groups of $n_s = 1, 2, 3$ and $\geq 4$. The values are shown in Table II.

<table>
<thead>
<tr>
<th>$n_s$</th>
<th>$\vec{p}_t$ (MeV/c)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>206.3±57</td>
</tr>
<tr>
<td>2</td>
<td>220.9±45</td>
</tr>
<tr>
<td>3</td>
<td>213.8±53</td>
</tr>
<tr>
<td>$\geq 4$</td>
<td>213.2±53</td>
</tr>
</tbody>
</table>

From the Table II it is evident that $\vec{p}_t$ is more or less constant for different groups of $n_s$ within error, which suggests that $\vec{p}_t$ is independent of shower multiplicity. Similar observations were reported by Malhotra\textsuperscript{118}, Shivpur\textsuperscript{122} and Ahmed et al\textsuperscript{117} in the $\pi$-nucleon, nucleon-nucleon and nucleon-nucleus collisions. Bhawmik et al\textsuperscript{150} reported that in the $\vec{P}$-nucleon interaction in the emulsion, the average transverse momentum ($\vec{p}_t$) depends upon multiplicity and that $\vec{p}_t$ increased with higher multiplicity.
Fig. 16: Variation of average $\bar{P}_t$ with laboratory emission angle
annihilation channels.

(e) **Number of neutral particles emitted during annihilation:**

For this purpose we calculated the average total energy \( E_H \) carried away by grey and black tracks in a star using the average values of \( N_{h_A} \), \( N_{g_A} \), \( N_{b_A} \) which are \((21.95 \pm 2.7)\), \((6.33 \pm 0.4)\) and \((16.0 \pm 2.2)\) respectively in the equation given by Powell et al. \(^8^3\).

\[
E_H = 2.2 \bar{E}_{g_A} N_{g_A} + \bar{E}_{b_A} (N_{b_A} + 4 \times 3N_{b_A}) + 8 (N_{b_A} + N_{g_A}).
\]

\( \bar{E}_{g_A} \), the average energy for grey tracks in the annihilation stars is found to be \((123 \pm 24)\) Mev.

\( \bar{E}_{b_A} \), the average energy for black tracks is taken to be equal to that for all the stars (Chapter III) i.e. \((8.8 \pm 0.9)\) Mev, because mean energy of evaporated protons was found to be similar for a wide range of values of the excitation energy. \(^8^3\) \( E_H \), therefore came out as \((3719 \pm 688)\) Mev.

Here, the average total energy of pions in an annihilation star is \( T_\pi = (327 + 140) = (467 \pm 35)\) Mev and that of kaons is \( T_K = (244 + 494) = (738 \pm 48)\) Mev, the average momentum of kaons being 541 Mev/c obtained by scattering measurement and then correcting for the whole sample of annihilation stars. The total visible energy is thus made up of \( E_H, T_\pi \) and \( T_K \) with proper weightage factor given to charged pions and kaons. The difference between the sum of these contributions and the total available energy \( W = 6035\) Mev, gives the mean value of the energy which is carried by neutral radiation, other than that of relatively slow neutrons of which account has been taken. The missing energy \((982 \pm 134)\) Mev
might be carried away by neutral pions and gamma rays. According to principle of charge independence, π⁺, π⁻, π⁰ mesons should, on the average, carry equal amount of energy. Therefore, the number of π⁰ mesons emitted per event is 2.1 ± .3 assuming the emission in the form of gamma rays is negligible. From this, ratio of total to charged pion emission i.e. \( \frac{N_{\pi^0}}{N_{\pi^\pm}} \) comes out as 1.86. This value is nearly equal to the observed ratio 1.8 obtained in other P-nucleon⁸⁹ and PP annihilations¹⁸.

(f) No of pions absorbed inside the nucleus :-

If the average number of pions absorbed inside the nucleus is designated by 'a', then the total number of charged and uncharged pions created in an annihilation is given by

\[
\bar{n} = \frac{2.43}{.97} + (2.1 \pm .3) + a
\]

where .97 ± .06 is efficiency for collection of shower particles.

Using the hydrogen bubble chamber data that on the average total number of pions produced in the PP annihilation is 7.3, we get

\[
7.3 \pm 0.6 = (4.6 \pm .38) + a
\]

or \( a = 7.3 - 4.6 = 2.7 \pm .7 \) i.e. on the average, two to three pions (charged + neutral) are absorbed inside the nucleus.

Again from the results of PP¹⁸ and P-nucleon⁸⁹ annihilation, we have
\[ \frac{N_\pi^0}{N_\pi^+} = 1.8 \]

Therefore, \( \bar{n} = \frac{1}{1.97} \times 1.8 \times 2.43 + a \)

i.e. \( 7.3 = 4.5 + a \)

or \( a = 7.3 - 4.5 = 2.8 \pm 0.64 \)

From these two results we may assume that, on the average, two to three pions are absorbed inside the silver or bromine nucleus during annihilation. Amaldi et al reported that average number of pions absorbed inside an average emulsion nucleus was \( 2.26 \pm 0.20 \).

4.4 Discussion

In the study of annihilation of antiprotons with heavy emulsion nuclei we observed that nearly 90\% of the created particles were pions and the rest 10\% are kaons, neglecting the production of hyperons which we did not observe in our study. The observed rate of kaon production in our experiment was the highest so far obtained in this energy range. The highest percentage that we obtained was probably due to correction of a few kaons that were actually observed.

The annihilation stars were characterized by a large number of cascade and evaporated particles due to large amount of energy available in the target nuclei. Emission of shower particles was also more in comparison to that observed for all the stars containing both annihilation and non-annihilation events (Chapter III). The average shower multiplicity, \( \bar{n}_{\text{sh}} = 2.7 \pm 0.2 \) for \( \bar{p} \)-nucleus annihilation
in our experiment, was less than that observed in the $\bar{P}$-nucleon annihilation\textsuperscript{89} ($\bar{n}_S^A = 4.1 \pm .5$) at the same incident momentum. On the other hand, at similar incident energy of 9 Gev, the average $n_S$ for $P$-Nucleon collision ($\bar{n}_S = 3.5 \pm .4$) was slightly more than that obtained in the $P$-nucleon collision ($\bar{n}_S = 2.9 \pm .3$) according to the report of Barashenkov et al\textsuperscript{35}.

Again in the $\bar{P}$-nucleus annihilation $\bar{n}_S^A$ decreased linearly with $N_{h_A}^A$, $N_{b_A}^A$ and $N_{g_A}^A$, the total heavily ionized, black and grey tracks respectively in a star; while the average shower multiplicity, $\bar{n}_S$, increased with total heavily ionized track, $N_h^A$ in a star in the $P$-nucleon\textsuperscript{88} and $P$-nucleus\textsuperscript{90} collisions. Thus the above facts about proton and antiproton interactions with nucleons and nuclei are contradictory. These contradictions arose probably due to different processes responsible for shower production in $\bar{P}P$ annihilation and $PP$ interactions. In $\bar{P}P$ annihilations, meson resonances are produced which decay mostly to pions and a few pairs of kaons; while in the $PP$ interactions, baryon resonances are produced which decay to nucleons and pions. Probably in the $P$-nucleus collisions, energetic nucleons among the shower particles are responsible for the production of more shower particles by secondary interactions in the outer core of the nucleus. Since energetic nucleons are absent in the annihilation process, there were almost no production of shower particles by secondary inte-
ractions. Hence there was no further rise of number of shower particles in the $\bar{P}$-nucleus annihilation. Moreover there was absorption of a few pions in the nucleus leading to decrease of average shower multiplicity in the $\bar{P}$-nucleus annihilation.

Thus it seems more probable that pions among the shower particles, cannot generally produce secondary shower particles in their turn because of their low energy. However, they can initiate cascading process leading to excitation of the nucleus. In the P-nucleus interactions, the increase of $n_s$ leads to increase of more secondary interactions in the target nucleus due to which it gets highly excited. Higher excitation results in the emission of larger number of heavy prongs. Thus, in the P-nucleus interactions there is always a slight increase of $N_h$ when $n_s$ increases. This increase of $N_h$ depends upon the atomic number of the target nucleus $^{35}$. In the $\bar{P}$-nucleus annihilations, on the other hand, only pions and a few kaons are produced. Here, we observe only those pions as shower particles, which are immediate result of the annihilation and escape after little or no interaction with the associated nucleus. This pions cannot generate further mesons by secondary interactions due to not very high energy available to them. Moreover, a few of them are absorbed in the nucleus so that if the number absorbed is large, $n_s$ is highly reduced and the disintegration becomes more violent with the emission of more heavy particles. Thus in the
P-nucleus annihilation, decrease of $\bar{n}_s$ leads to increase of $N_h$, i.e., increase of both $N_g$ and $N_b$. It can be mentioned here that in the interaction with silver and bromine nuclei, the heavy prong multiplicity and shower multiplicity were found to be $(10.2 \pm 0.4)$ and $(3.5 \pm 0.4)$ at 9 Gev proton interactions and $(21.95 \pm 2.7)$ and $(2.7 \pm 0.3)$ at 5 Gev/c P-nucleus annihilation.

As in the cosmic ray stars, we also observed that the mean-energy of particles producing grey tracks (protons in our case) was nearly independent of the type of stars (annihilation or non-annihilation) from which they emerged. The average energy of protons producing grey tracks in the annihilation stars was $(123 \pm 24)$ Mev, while in the stars of combined annihilation and non-annihilation events, it was $(110 \pm 12.5)$ Mev. (Chapter III).

In the study of P-nucleon annihilation at 5 Gev/c, Bhowmik et al. observed that the average transverse momentum, $p_t$, of pions depended on shower multiplicity, and that $\bar{p}_t$ increased with higher shower multiplicity. They explained it to be due to $\rho$ production at high multiplicity events. Pions from $\rho$ have a larger mean value of $p_t$ than that of the decay pions from $\omega$, which is produced at low multiplicity. This is contradictory to our observation that in the P-nucleus annihilation, $\bar{p}_t$ was independent of $n_s$. Such a contradiction is not unexpected from the fact that the momenta of the pions were modified due to the presence of other nucleons in the nucleus.
in such a way that $\bar{p}_t$ appeared to be independent of $n_\pi$. In the nucleon-nucleon, pion-nucleon and proton-nucleus interactions, $\bar{p}_t$ was found to be independent of $n_\pi$. In these cases of non-annihilation, both low and high multiplicity events contribute equally to $\bar{p}_t$, because the production of nucleon isobars and antiisobars was equally dominant. For the same reason that $\bar{p}_t$ was independent of $n_\pi$, the nature of variation of $\bar{p}_t$ with angle of emission of pions in the nucleon-nucleon, prion-nucleon, proton-nucleus interactions and $\bar{P}$-nucleus annihilations were almost similar.

From the calculation of total energy released in an average annihilation star with the assumption that gamma-ray emission was negligibly small, the average number of neutral pions emitted per annihilation event came out as $2.1 \pm .3$. This gave the ratio of total to charged pion production per interaction as $1.86$. This value is nearly equal to $1.8$ - a value obtained for $\bar{PP}$ and $\bar{P}$-nucleon annihilations.

In the $\bar{P}$-nucleon annihilation in emulsion, on the average $(4.0 \pm .6)$ charged pions are emitted; while in the $\bar{P}$-nucleus annihilation in our experiment we observed average pion multiplicity as $(2.43 \pm .13)$. Assuming that on the whole, $(7.3 \pm .6)$ pions (neutral + charged) are produced in $\bar{PP}$ annihilation (obtained from H.B.C. data), we calculated that on the average two to three pions should be absorbed inside a silver or bromine nucleus.

4.5 **Summary** :-

(1) The equation used here for total energy
calculation in the stars is based on cascade-evaporation model of the nucleus. It is assumed in this model that excitation energy is always less than the total binding energy of the nucleus. Such assumption is not always found to be true although this model is the best fitted one to explain the facts at this incident momentum.

(2) Annihilation stars are much larger, indicating that a sizable portion of the incident energy is used up in disintegrating the nucleus. The mean number of heavily ionised tracks in a star is \( \bar{N}_h = 21.95 \pm 2.7 \). In a few stars \( N_h \) is as large as 38, where excitation energy exceeds the total binding energy of the silver nucleus. Probably in these stars complete disintegration took place almost instantaneously in a single stage process.

(3) In the nucleon-nucleon or nucleon-nucleus interactions \( \bar{n}_s \) rises with \( N_h \), while in the annihilation, the reverse is the true. It is because of different processes of production of pions in the two types of interactions. In the former, mainly baryon resonances and in the latter meson resonances are produced.

(4) Angular distributions of pions among the shower particles were found to be symmetric and not so broad as that for all the stars (Chapter III).

(5) The average number of neutral pions emitted per interaction was calculated to be 2.1 which made the ratio \( \frac{N_{\pi^0}}{N_{\pi^+}} \) equal to 1.86. This value was similar to 1.2 obtained
from H.B.C. data.

(6) From the independence of average $p_t$ on shower multiplicities and from dependence of average $n_s$ on $N_b$, $N_e$, and $N_h$ respectively, we assume that pions among cascade the shower particles really take part in secondary interactions inside the nucleus in the annihilation process. Some of the pions are even absorbed making the disintegration more violent. From our observation, it appears that on the average 2 to 3 pions are absorbed per interaction.