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I.V.Boguslavsky, I.M.Gramenitsky, V.Karimäki,
I.A.Korzhavina, R.Orava, L.A.Tikhonova

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I.V.Boguslavsky, I.M.Gramenitsky, V.Karimaki,[1]
I.A.Korzhavina,[2] R.Orava,[1] L.A.Tikhonova

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[1] University of Helsinki, Helsinki, Finland.
[2] Institute for Nuclear Physics Research of the Moscow State University, Moscow, USSR.

1. INTRODUCTION

The determination of the annihilation cross section is an important problem in antiproton-proton experiments (see, e.g.,[1]). At low energies the annihilation and non-annihilation channels can be separated rather well by means of kinematic fitting, whereas at high energies ($P \geq 10$ GeV/c) this method is practically impossible due to an increasing number of neutral and charged secondary particles.

A few attempts to separate annihilation events have been made at higher energies. Everett et al. have described technique[2] which makes use of the charge conjugation symmetry of antiproton-proton interactions.

The method was applied to antiproton-proton experiments at 4.6 and 9.2 GeV/c.

In this article we discuss a completely different approach to the problem. The described method is based on the observation of secondary collisions in primary $\bar{p}p$-interactions in the bubble chamber. The method is based on the fact that the rate of secondary interactions per event is a function of the average number of nucleons and anti-nucleons per event, and at rather high energies the

Np and $\bar{N}$p cross sections are considerably higher than the πp and Kp ones (see fig. 1).

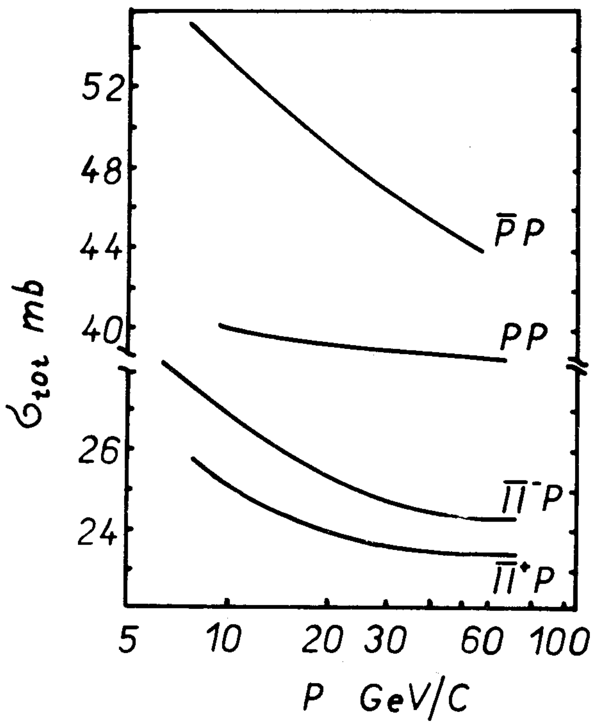

Fig. 1. Total cross sections of different particles as a function of primary momentum.

Having determined the average multiplicity of nucleons and antinucleons from the number of secondary interactions, one can then calculate the annihilation cross section.

2. OUTLINES OF THE METHOD

For simplicity, consider first a monochromatic beam of antiprotons and π^--mesons colliding with a hydrogen target. The fraction of antiprotons in the beam is assumed to be a constant value denoted by α. Then the effective interaction cross section of such a mixed beam on hydrogen can be written as

$$\sigma_{eff} = \alpha\sigma_{\bar{p}p} + (1-\alpha)\sigma_{\pi^-p} = \sigma_{\pi^-p} + \alpha\,\Delta\sigma , \qquad (1)$$

where $\sigma_{\bar{p}p}$ and σ_{π^-p} are the total antiproton and π^--meson cross sections on hydrogen, respectively, and $\Delta\sigma$ is their difference. Measuring σ_{eff} and knowing the cross sections $\sigma_{\bar{p}p}$ and σ_{π^-p}, one can determine the fraction

$$\alpha = \frac{1}{\Delta\sigma}\,(\sigma_{eff} - \sigma_{\pi^-p}) . \qquad (2)$$

It is obvious that the accuracy of determination of α depends on the difference $\Delta\sigma$. In the extreme case, when $\Delta\sigma = 0$, one cannot at all obtain information on the beam structure in this way.

Equations (1) and (2) can be used to determine the fraction of antiprotons in negative secondary tracks created in $\bar{p}p$-interactions. Of course, the idea can be also applied to protons, as according to charge conjugation symmetry of $\bar{p}p$-interactions, the average antiproton multiplicity equals the average proton one. But we restrict ourselves to consideration of only negative tracks as motivated by the fact that the difference $\Delta\sigma$ for proton and π^+-meson is smaller than the difference for their antiparticles (see fig. 1).

The value σ_{eff} for secondary negative tracks can be obtained from the observed number of interactions among negative secondaries according to the formula

$$N_s^- = \rho L \sigma_{eff} N^- = \rho L \sigma_{eff} \langle N^- \rangle N_{eV} , \qquad (3)$$

where ρ is the number of target protons per cm^3, L is the potential lenght of the secondary track (see fig. 2), N^- is the total number of negative secondary particles, N is the total number of primary $\bar{p}p$ -interactions, and $\bar{N^-} = N^- / N_{eV}$ is the average number of negative secondaries per event.

From (1) and (3) we readily derive

$$\alpha N^- = \frac{1}{\rho L \Delta\sigma} N_s^- - \frac{\sigma_{\pi^- p}}{\Delta\sigma} N^- . \qquad (4)$$

In the real situation we have not the monochromatic beam of secondary particles, but the momentum spectrum. This is the reason why we have to take into account the fact that the quantities σ_{eff} , L , α in formula (4) depend on the track momentum $\vec{p}$ as well as on the position $\vec{r}$ of the primary interaction vertex. Then we have

$$\alpha(\vec{p})\, dN^-(\vec{p},\vec{r}) = \frac{dN_s^-(\vec{p},\vec{r})}{\rho L(\vec{p},\vec{r})\, \Delta\sigma(\vec{p})} - \frac{\sigma_{\pi^- p}(\vec{p})}{\Delta\sigma(\vec{p})} dN^-(\vec{p},\vec{r}) . \qquad (5)$$

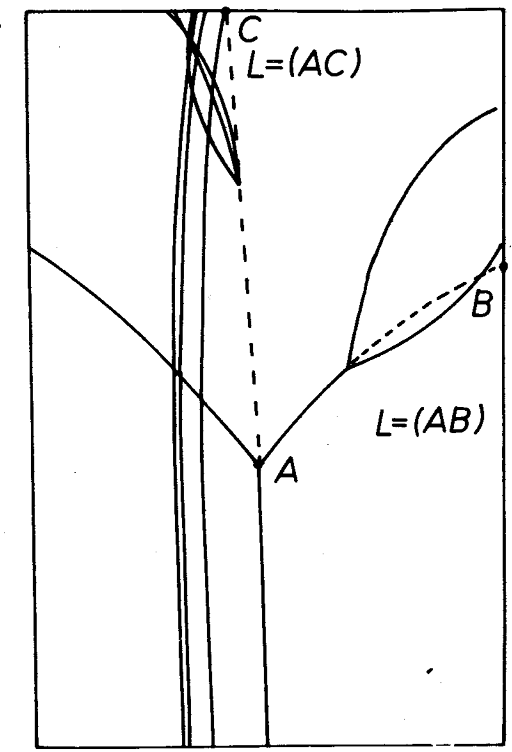

Fig. 2. Secondary interactions in the bubble chamber pictures.

Now considering $dN^-(\vec{p},\vec{r})$ and $dN_s^-(\vec{p},\vec{r})$ as six-dimensional probability densities normalized to N^- and N_s^- , respectively, we obtain by integrating eq. (5)

$$\langle \alpha \rangle = \frac{N_s^-}{N_{eV} \langle N^- \rangle \rho} \left\langle \frac{1}{L \Delta\sigma} \right\rangle_s - \left\langle \frac{\sigma_{\pi^- p}}{\Delta\sigma} \right\rangle , \qquad (6)$$

where $\langle\ \rangle_s$ and $\langle\ \rangle$ mean the averaging over the probability densities $dN_s^-(\vec{p},\vec{r})$ and

$dN_s^-(\vec{p},\vec{r})$, respectively. In connection with a finite number of observed events in an experiment, the equation (6) leads to the following simple expression for the mean antiproton multiplicity:

$$\langle N_{\bar{p}} \rangle = \langle \alpha \rangle \langle N^- \rangle = \tag{7}$$
$$= \frac{1}{N_{eV}} \{ \frac{1}{\rho} \sum_s [L(\vec{p},\vec{r})\,\Delta\sigma(\vec{p})]^{-1} - \sum_t [\sigma_{\pi^- p}(\vec{p})/\Delta\sigma(\vec{p})] \},$$

where $\sum_s$ means a sum taken over the negative tracks with observed secondary interactions and $\sum_t$ a sum over all the negative secondary tracks.

Let us now consider all inelastic channels which make a main contribution to the $\bar{p}p$ - cross section

$$\bar{p}p \longrightarrow \bar{p}p + \ldots \tag{8a}$$
$$\longrightarrow \bar{p}n + \ldots \tag{8b}$$
$$\longrightarrow \bar{n}n + \ldots \tag{8c}$$
$$\longrightarrow \bar{n}p + \ldots \tag{8d}$$
$$\longrightarrow m\pi + c\,k \quad \text{(annihilation)} \tag{8e}$$

Having determined $\langle N_{\bar{p}} \rangle$ for inelastic reaction by the formula (7), one can estimate the sum of the cross sections (8a) and (8b). Thus the upper limit for the annihilation cross section is derived as follows

$$\sigma_{ann} < \sigma_{tot}^{in} - \sigma(8a+8b) = \sigma_{tot}^{in}\,(1 - \langle N_{\bar{p}} \rangle), \tag{9}$$

The accuracy of the derived cross section σ (8a + 8b) depends on the number of secondary interactions observable in the bubble chamber. This will be discussed in more detail in chapter 3.

In principle, use could be made of the same technique for determining the average multiplicity of neutrons and antineutrons by observing neutral secondary interactions or neutral stars. In the same way, as we derived eq. (7), we obtain

$$\langle N_{\bar{n}} \rangle = \langle N_n \rangle = \frac{1}{\rho\, N_{eV}} \; \frac{\sum_s L(\vec{p},\vec{r})^{-1}}{\langle \sigma_n \rangle + \langle \sigma_{\bar{n}} \rangle}, \tag{10}$$

where the quantities ρ, N_{eV} and L are defined as in eq. (3) and $\langle \sigma_{\bar{n}} \rangle$, $\langle \sigma_n \rangle$ are the $\bar{n}p$ and np cross sections averaged over the laboratory momentum spectrum of antineutrons and neutrons, respectively. The annihilation cross section can finally be calculated from the formula

$$\sigma_{ann} = \sigma_{tot}^{in}\,[1 - (\langle N_{\bar{p}} \rangle + \langle N_{\bar{n}} \rangle)]. \tag{11}$$

However, many practical difficulties and complications arise, especially in the application of formula (10). This matter is also considered in the following chapter.

3. DISCUSSION OF THE METHOD

In order to have an idea of the statistical accuracy of formula (7), we consider its application to the $\bar{p}p$ -experiment at 22.4 GeV/c in the "Ludmila" bubble chamber[3].

In this experiment, typical values for L and $\langle N^- \rangle$ are L = 50 cm and $\langle N^- \rangle \mp 2.5$. For simplicity, we assume $\Delta\sigma = \sigma_{\bar{p}p} - \sigma_{\pi^- p} \approx 20$ mb. Furthermore, assuming a constant relative error for the fraction α , $\delta\alpha = 10\%$, we compute the numbers listed in the table for different α -values.

Table

	$\alpha = 0{,}3$	$\alpha = 0{,}2$	$\alpha = 0{,}1$	$\alpha = 0{,}05$
1) σ_{eff}(mb)	36	34	32	31
2) $\delta\sigma_{eff}$(%)	1.7	1.2	0.6	0.3
3) $\delta\sigma$ (8a + 8b) (%)	30	10	3.3	1.4
4) $N_s \cdot 10^3$	3.6	7.0	25.0	31.0
5) $N_{eV}\, 10^3$	22.0	46.0	172.0	220.0

The statistical accuracy of formulá (10) appears to be always better than that of formula (7). This is connected with that nuetral pions do not contribute to neutral secondary interactions due to their very short life time. On the other hand, there exist a few practical complications when we want to apply the formula (10). First of all, the momentum spectra of neutrons and antineutrons are unknown, as a rule, and it is necessary to make some assumptions about their forms. Secondly, there may be some admixture of neutrons connected with the primary antiproton beam. Both these facts lead to sizable uncertainty in $\langle N_{\bar{n}} \rangle$.

Another complication of the method consists in the fact that not all the secondary particles are nucleons and pions. A part of antibaryon - baryon pairs in the final state involves hyperons or antihyperons and a fraction of mesons are kaons. Fortunately, this is not a serious problem, since hyperon production in the cross section is rather small (roughly 10%) and may be neglected in the first approximation. On the other hand, hyperons can be identified by their visible decays and can therefore be taken into account in more accurate calculations.

As for kaons their influence on formula (7) is also negligible because the Kp-cross section is only slightly different from the πp -cross section.

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