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ANTIPROTON-HELIUM ANNIHILATION AROUND 44 MeV/c

F. Balestra, S. Bossolasco, M.P. Bussa, L. Busso, L. Ferrero,
D. Panzieri, G. Piragino and F. Tosello
Istituto di Fisica Generale 'A. Avogadro', University of Turin and
INFN, Sezione di Torino, Turin, Italy

R. Barbieri, G. Bendiscioli, V. Filippini, A. Rotondi, P. Salvini and A. Zenoni
Dipartimento di Fisica Nucleare e Teorica, University of Pavia and
INFN, Sezione di Pavia, Italy

Yu. A. Batusov, I.V. Falomkin, G.B. Pontecorvo, A.M. Rozhdestvensky
M.G. Sapozhnikov and V.I. Tretyak
Joint Institute for Nuclear Research, Dubna, USSR

C. Guaraldo and A. Maggiora
Laboratori Nazionali di Frascati dell'INFN, Frascati, Italy

E. Lodi Rizzini
Dipartimento di Automazione Industriale, University of Brescia and
INFN, Sezione di Pavia, Italy

A. Haatuft, A. Halsteinslid, K. Myklebost and J.M. Olsen
Physics Department, University of Bergen, Norway

F.O. Breivik, T. Jacobsen and S.O. Sørensen,
Physics Department, University of Oslo, Norway

Abstract - The $\bar{p}^4\text{He}$ annihilation cross section averaged over the interval 40-48 MeV/c has been measured in the PS-179 experiment at the LEAR facility of CERN using a streamer chamber in a magnetic field. The measured value is $(1467 \pm 320)\text{mbarn}$. It agrees with a behaviour like $1/v$ of the annihilation cross section. Our result has been obtained at the lowest momentum achieved till now in measurements of antiproton annihilation in flight.

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1. Introduction

In this paper we report the measurement of the annihilation cross section of antiprotons on ^4He in the momentum range from 40 to 48 MeV/c (0.85-1.23 MeV). The present data integrate the results obtained by our collaboration in the PS-179 experiment at the LEAR facility of CERN at the three momenta 192.8, 306.2 and 607.7 MeV/c, and at rest [1-3].

Annihilation events were detected with a self-shunted streamer chamber ($90 \times 70 \times 18 \text{ cm}^3$) in a magnetic field (0.409 T in this measurement) filled with gaseous helium (pressure $\simeq 1 \text{ atm}$, temperature $\simeq 300^\circ\text{K}$, mean density $\simeq 1.57 \cdot 10^{-4} \text{ g/cm}^3$); the chamber served both as a target and as a detector. The events were recorded on pair of photographic films. The gas temperature and pressure were continuously under control during the runs, and their variations affect by less than 2% the gas density. The experimental apparatus is described in detail in ref. [4] and the procedure for the event reconstruction is discussed in detail in ref. [5].

The high quality of the LEAR $\bar{p}$ beam (initial momentum 105.2 MeV/c, $\Delta p/p = 10^{-4}$) and the low density of the gas target permitted a first investigation of annihilations in flight at a very low energy (lower than 60 MeV/c) where hitherto there existed no experimental values. It is noteworthy that annihilation is the only inelastic reaction occurring at such a low energy and annihilations at rest are by far more probable than those in flight (by a factor of about 10^3). Problems related to the measurement of antiproton cross sections at these energies are discussed, for instance, in Ref. 6.

The events were detected in a central fiducial region of the sensitive volume ($\pm 22.5 \text{ cm}$ around the center of the chamber), where the detection efficiency is close to 100%. We scanned 97226 pictures, each with a sole $\bar{p} \text{ } ^4\text{He}$ annihilation event.

Antiprotons from LEAR lose energy in beryllium and mylar windows, in thin scintillation counters and in some centimetres of air before the entrance to the gas target. At the entrance to the chamber the mean momentum is about 61.3 MeV/c. The momentum distribution measured at a distance $x_0 = 22.5 \text{ cm}$ from the entrance to the chamber is reported in Fig. 1. We counted on a projected view all the antiprotons arriving at x_0 and measured the momentum of a sample. As the beam is spread in space, the choice of the reference line on a projected view produces a further spread in the beam momentum. However this is small compared to the intrinsic spread of the beam. We measured one antiproton track every 50 pictures. The statistical error on the momentum is due to the pointing errors on the measurement table and to the multiple scattering and the straggling in the energy loss. The former was estimated by repeated measurements to be less than 2% for tracks with momentum between 40 and 60 MeV/c (see also Ref. 5). Correspondingly, the error due to the other effects was estimated to be of order of $\pm 1 \text{ MeV/c}$ through a Montecarlo simulation.

2. Identification of the annihilations in flight.

To identify the annihilation events in flight (our goal was to select events with antiproton momentum higher than 40 MeV/c) we proceeded in two steps. Firstly, we selected the annihilations with antiproton momentum roughly higher than 35 MeV/c. This was obtained by comparing on the scanning table all the projected tracks from one stereoscopic view with a reference track drawn on a template. This reproduces the mean features of projected tracks with momentum, at the end point, close to 35 MeV/c. In our magnetic field, the curvature of the stopping tracks differs remarkably from that of the reference track (see Fig. 2). As the momentum at the annihilation point approaches 35 MeV/c, the behaviour of the tracks approaches gradually that of the reference track. So, due also to stereoscopic effects (the tracks have different directions in space), fluctuations of the luminosity and other features, the identification of the events with antiproton momentum >35 MeV/c is not sharp. However, 35 MeV/c is an enough low threshold to prevent that annihilations at 40 MeV/c and above can be discarded. By this quick procedure, over a total of $\sim 10^5$ events, we selected $2.5 \cdot 10^3$ events.

In a second step, we measured repeatedly the selected events following the criteria described in Ref. 5, in order to determine carefully the momentum at x_0 and at the annihilation point. It turned out that 34 events are annihilations in flight with momenta between 40 and 54 MeV/c.

In fitting the tracks, care was taken to avoid errors due to elastic scattering, especially in the last centimetres of the tracks, which results in a momentum value either lower or higher than the real one. Tracks affected by elastic scattering are characterized by high values of the reduced χ^2 of the fitting procedure. Annihilation events preceded by elastic scattering were rejected. The error on the momentum coming from the pointing errors, for the selected 34 in-flight annihilation events, was estimated to be (1.49 ± 0.91) MeV/c by repeated measurements. The error due to the multiple scattering and to the straggling in the energy loss is of the same order of magnitude of that on the initial momentum (about 1 MeV/c, see Sect. 1).

3. Evaluation of the cross section averaged over a momentum interval.

We intend to measure the mean value of the annihilation cross section over a momentum interval $(p_{\min}, p_{\max})$. Therefore, with reference to the momentum distribution of Fig. 1, let us consider the antiprotons with momentum $p > p_{\max}$; their number is $n(p > p_{\max})$.

The number of the events produced by these $\bar{p}$ is

$$N_{ev}(p_{min}, p_{max}) = n(p > p_{max}) \rho \int_{p_{max}}^{p_{min}} \sigma(p) \frac{ds}{dp} dp \quad (1)$$

where $\sigma(p)$ is the annihilation cross section, ρ the number of target nuclei/cm³ and s a coordinate along a track.

We calculate eq. (1) in an approximate way by substituting $\sigma(p)$ with its value averaged over (p_{min}, p_{max}) :

$$\bar{\sigma}(p_{min}, p_{max}) = \frac{1}{p_{max} - p_{min}} \int_{p_{min}}^{p_{max}} \sigma(p) dp$$

Hence

$$N_{ev}(p_{min}, p_{max}) = n(p > p_{max}) \rho \bar{\sigma}(p_{min}, p_{max}) \int_{p_{max}}^{p_{min}} \frac{ds}{dp} dp \quad (2)$$

The integral at the right side of this equation is the length of the part of each track where the $\bar{p}$ momentum decreases from p_{max} down to p_{min} , i.e. the length of the effective target relative to the chosen momentum interval. Introducing the energy loss per unit length relation $(-dE/ds)$, the length of the effective target is

$$S = \int_{p_{max}}^{p_{min}} \frac{ds}{dp} dp = \int_{E_{min}}^{E_{max}} \frac{dE}{\left(-\frac{dE}{ds}\right)} = R(p_{max}) - R(p_{min}) \quad (3)$$

where $R(p)$ is the range. Hence, by eqs. (2) and (3), one has

$$N_{ev}(p_{min}, p_{max}) = n(p > p_{max}) \rho S \bar{\sigma}(p_{min}, p_{max}) \quad (4)$$

and

$$\bar{\sigma}(p_{min}, p_{max}) = \frac{N_{ev}(p_{min}, p_{max})}{\rho S n(p > p_{max})} \quad (5)$$

The error due to the approximate eq. (4) with respect to eq. (1) can be estimated by assuming for $(-dE/ds)$ a dependence on the momentum as $1/p^2$ (from the Bethe formula) and for $\sigma(p)$ a dependence as $1/p$ (see later on) and calculating N_{ev} by the two equations. One finds that, in the momentum intervals of interest here, the value obtained through eq. (4) is underestimated by less than 1%. As a consequence, $\bar{\sigma}$ deduced from

eq. (5), where N_{ev} is the experimental number of events (i.e., the true number), is overestimated by less than 1%.

Now we calculate $\bar{\sigma}$ around 45 MeV/c through eq. (5). To this aim, we note that the statistical error on $\bar{\sigma}$ depends on the poor statistics concerning N_{ev} , on the error on the momentum due to the pointing error (few percentage on the incoming momentum and about 1.5 MeV/c on the annihilation momentum), and on the error on the momentum due to the multiple scattering and the straggling in the energy loss (about 1 MeV/c).

In order to evaluate the whole error, we observe that for not too large intervals Δp centered around the same value p_0 and for a behaviour of σ as a function of p similar to that for $\bar{p}p$ annihilation ($\sigma \propto 1/p$), the value of $\bar{\sigma}$ is practically independent of Δp and $\bar{\sigma} \simeq \sigma(p_0)$. Moreover, for $\sigma \propto 1/p$, by varying p_0 between 43 and 47 MeV/c, the value of σ changes at most by 4.4% with respect to the value around 45 MeV/c.

Following these considerations, we have calculated $\bar{\sigma}$ for different intervals centered around 45 MeV/c and for single intervals around 42, 43, 44, 46 and 47 MeV/c. Also disjoint intervals were considered. The values of $\bar{\sigma}$ are spread between 1131 and 1739 mb and the differences are compatible with the percentage statistical errors on N_{ev} (N_{ev} , within the different intervals, varies from 8 to 24 and the error from 35.3% to 20.4%). All this considered, we assumed that a value of $\bar{\sigma}$ representative of all our measurements is that obtained from the interval $\Delta p=40-48$ MeV/c, for which $N_{ev}=21$, $n(p>48)=70559$ and $S=8.58$ cm; that is

$$\bar{\sigma}(40,48) = (1468 \pm 324)\text{mb}$$

where the error corresponds to the percentage error $1/\sqrt{21}$. The systematic error arises mainly from the uncertainty on p and is negligible in this context.

In Fig. 3 our result is reported together with other results on $\bar{n}p$, $\bar{p}p$, $\bar{p}d$, $\bar{p}^3\text{He}$ and $\bar{p}^4\text{He}$ annihilations in flight: one can see that the $\bar{p}^4\text{He}$ annihilation cross section at 200 MeV/c amounts to about 0.25 of that obtained in this work, showing a rough dependence as $1/v$.

We note that in the interval 200-600 MeV/c the annihilation cross section on ^4He is close to twice that on hydrogen (see Fig. 3). No data on $\bar{p}p$ annihilation exist at lower energy, but recently Mahalanabis et al. [13] have obtained the behaviour of the $\bar{p}p$ annihilation cross section down to zero energy, by fitting $\bar{p}p$ and $\bar{n}p$ total, elastic, annihilation and charge exchange cross sections below 300 MeV/c as well as the energy shift and width of the antiprotonic hydrogen (see Fig. 3). At 44 MeV/c they find $\sigma=750$ mb. About the same value at 43 MeV/c has been measured in an $\bar{n}p$ annihilation experiment [14] (see Fig. 3). Therefore also around 44 MeV/c, the $\bar{p}^4\text{He}$ annihilation cross section is approximately twice that for free nucleon.

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FIGURE CAPTIONS

Fig. 1 - Beam momentum distribution measured at the beginning of the fiducial volume (22.5 cm from the entrance to the chamber) and range vs. momentum for a gas density of $1.57 \cdot 10^{-4} \text{ g/cm}^3$.

Fig. 2 - Typical annihilation event at rest (full lines). The curvature of the antiproton track is compared with that of a track which in its last point (the vertex of the event) corresponds to a momentum of 35 MeV/c (dashed line).

Fig. 3 - Annihilation cross section for different nuclei.

$\bar{p}p$: (—) best fit line over experimental data from Ref. 9 including annihilation into neutrals (see Ref. 10); (-.-) line from $\bar{p}p$ and $\bar{n}p$ data analysis of Ref. 13.
 $\bar{n}p$: (---) best fit line over experimental data from Ref. 11; (□) data from Ref. 14.

$\bar{p}^2\text{H}$: data from Ref. 7 (○) and ref. 8 (●).

$\bar{p}^3\text{He}$: (■) from Ref. 11.

$\bar{p}^4\text{He}$: (Δ) from Ref. 3 and this work (at 44 MeV/c). The dotted line is a guide for the eye according to eq. $\sigma(p)=132+52711/p$.

Fig. 1.

Fig. 2

Fig. 3