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INELASTIC INTERACTION OF ANTIPROTONS WITH ^{4}He NUCLEI BETWEEN 200 AND 600 MeV/c

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The antiproton–helium reaction cross section has been measured at 19.6 and 48.7 MeV with a streamer chamber in a magnetic field. Charged prongs and negative pion multiplicities and cross sections for the production of ^{3}He are given. A comparison with $\bar{p}\ ^2$H is performed. The previously obtained 179.6 MeV results are also taken into account.

In a previous paper [1] we reported some experimental results on the inelastic interaction of 179.6 MeV antiprotons with ^{4}He nuclei. Here we present new results obtained at 19.6 and 48.7 MeV (192.8 and 306.2 MeV/c, respectively).

The research was performed by means of a self-shunted streamer chamber in a magnetic field [2] exposed to the antiproton beam of the LEAR facility at CERN.

The results were obtained by simply counting the inelastic events and the charged prongs, distinguishing the negative particles from the positive ones. The reaction $\bar{p} + {}^4\mathrm{He} \to V^0 + X (V^0 = K^0_s, \Lambda)$ was identified through the decay modes.

The detection efficiency of the chamber was determined through repeated measurements. It turned out to be about 100% for those events whose vertices were occurring in the 80 cm long central region of the chamber. Such a high efficiency was due to the presence of at most one event per photogram, a fact which makes the vertex recognition very easy. In measuring the total charged prong multiplicity the fiducial region was reduced to a 55 cm long central zone, far from the chamber walls, so as to maintain the same detection efficiency for a prong emitted in the forward (or backward) direction.

Moreover, it was checked that for a given event the same number of charged prongs was assigned by differ-

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ent scanners in 96.5% of the cases. In the remaining cases an uncertainty of ±1 prongs – due to track shortness and/or spatial orientation – was observed. We assigned to these events the more probable multiplicity resulting from the repeated scanning procedures.

The possible ($\bar{p}$, ^{4}He) reaction channels are listed in table 1 and include $\bar{p}p$ charged exchange, inelastic scattering (break-up and knock-out), annihilation with emission of pions followed by pion–nucleon interaction. Elastic events were checked through coplanarity measurements.

Table 1
($\bar{p}$, ^{4}He) reaction channels: "annihilation" ≡ annihilation preceded by initial state interaction and/or followed by final state interaction; "annihilation + ch. exch." ≡ annihilation preceded by charge exchange ($\bar{p}p \to \bar{n}n$) or by pion charge exchange ($\pi^- p \rightleftarrows \pi^0 n$, $\pi^0 p \rightleftarrows \pi^+ n$). Strange particle production has not been taken into account.

Number of charged prongs	($\bar{p}$, ^{4}He) reaction products [a)]	Reaction type	N_{π^-}
1	t+$\bar{n}$+n	charge exchange	0
1	X+$\bar{n}$+Nn	charge exchange + break-up	0
1	t+$M\pi^0$	$\bar{p}p$ annihilation	0
1	X+Nn+$M\pi^0$	annihilation	0
1	3n+π^++$M\pi^0$	annihilation + ch.exch.	0
2	$\bar{p}$+^{4}He	elastic scattering	0
2	$\bar{p}$ ^{3}He+n	knock-out	0
2	^{3}He+π^-+$M\pi^0$	$\bar{p}n$ annihilation	1
3	$\bar{p}$+2X+Nn	break-up	0
3	$\bar{p}$+t+p	knock-out	0
3	2X+π^-+Nn+$M\pi^0$	annihilation	1
3	t+2$\pi^\pm$+$M\pi^0$	$\bar{p}p$ annihilation	1
3	X+2$\pi^\pm$+Nn+$M\pi^0$	annihilation	1
3	3$\pi^\pm$+3n+$M\pi^0$	annihilation + ch.exch.	1
4	^{3}He+3$\pi^\pm$+$M\pi^0$	$\bar{p}n$ annihilation	2
5	2X+3$\pi^\pm$+Nn+$M\pi^0$	annihilation	2
5	t+4$\pi^\pm$+$M\pi^0$	$\bar{p}p$ annihilation	2
5	X+4$\pi^\pm$+Nn+$M\pi^0$	annihilation	2
5	5$\pi^\pm$+3n+$M\pi^0$	annihilation + ch.exch.	2
5	3X+2π^-+$M\pi^0$	annihilation + ch.exch.	2
6	^{3}He+5$\pi^\pm$+$M\pi^0$	$\bar{p}n$ annihilation	3
7	2X+5$\pi^\pm$+Nn+$M\pi^0$	annihilation	3
7	t+6$\pi^\pm$+$M\pi^0$	$\bar{p}p$ annihilation	3
7	X+6$\pi^\pm$+Nn+$M\pi^0$	annihilation	3
7	7$\pi^\pm$+3n+$M\pi^0$	annihilation + ch.exch.	3
7	3X+4$\pi^\pm$+$M\pi^0$	annihilation + ch.exch.	3
8	^{3}He+7$\pi^\pm$+$M\pi^0$	$\bar{p}n$ annihilation	4

a) X = p, d, $0 \leqslant N \leqslant 2$, $M \geqslant 0$.

The total charge of the ($\bar{p}$, ^{4}He) system being odd (+1), it follows that $\bar{p}$ annihilation on one neutron gives rise to reactions with an even number of prongs involving recoil ^{3}He particles. Initial and final state interactions can break the ^{3}He nucleus in such a way as to enrich the odd-prong channels.

It is noteworthy that threshold energies in the laboratory system for break-up and knock-out reactions ($\bar{p}^4$He → $\bar{p}$pt) and charge exchange ($\bar{p}^4$He → $\bar{n}$nt) are, respectively, 26.6 MeV and 28.1 MeV. Therefore, annihilation is the only inelastic process that takes place at 19.6 MeV.

It must be also recalled that the measurement of the production rate of different heavy particles such as ^{2}H, ^{3}He is of great interest in cosmology, since it may impose limits on the possible amount of antiprotons in the early universe and consequently severe constraints on the concentration of unstable partlces weighing 10–10^3 GeV which decay after primordial nucleosynthesis [3]. Results of our collaboration on the argument are reported in ref. [4].

In table 2 the total reaction cross sections and the cross sections for the different reaction channels are given, together with the mean numbers of charged prongs. A systematic error less than about 2.5% – due to uncertainties in the target transparency and the dose measurements – was estimated for the total reaction cross sections; at the same time, systematic errors less than about 3.5% – due to uncertainties in the prong multiplicity measurements – were estimated for the cross section of the different reaction channels.

The energy behaviour of the ($\bar{p}$, ^{4}He) reaction cross section is compared in fig. 1 with the reaction cross section values for hydrogen and deuterium. It is interesting to note that at 300 MeV/c the ($\bar{p}$, ^{4}He) and ($\bar{p}$, ^{2}H) cross sections have about the same values, but, as the $\bar{p}$ energy decreases, the reaction cross section seems to increase in deuterium more rapidly than in hydrogen and in ^{4}He.

Reaction cross section data allows one to obtain information on the annihilation ratio $R = \sigma_{\bar{p}n}/\sigma_{\bar{p}p}$ through a Glauber theory which describes $\bar{p}$–nucleus scattering data surprisingly well down to 300 MeV/c, as was shown by Dalkarov and Karmanov [8,9]. By using the standard Glauber theory [10], we fitted the 600 MeV/c

Table 2
Total reaction cross section, cross section for reactions with different number of charged prongs and for ^{3}He production. All quantities are in mb. $\langle n_c \rangle$ is the mean number of charged prongs per event.

Number of charged prongs	σ 19.6 MeV	48.7 MeV	179.6 MeV	N_{π^-}
1	19.30 ± 3.5	15.7 ± 2.1	16.4 ± 1.9	0
2	27.3 ± 4.2	15.4 ± 2.1	9.8 ± 1.4	0,1
3	125.8 ± 9.1	94.7 ± 5.1	72.9 ± 3.9	0,1
4	53.2 ± 5.9	31.9 ± 2.9	20.0 ± 2.1	2
5	148.5 ± 9.9	103.4 ± 5.4	90.6 ± 4.4	2
6	11.9 ± 2.8	10.6 ± 1.7	5.5 ± 1.1	3
7	18.0 ± 3.4	21.0 ± 2.4	17.7 ± 2.0	3
8	0.65 ± 0.65	0.56 ± 0.4	0.4 ± 0.3	4
9	0.65 ± 0.65	0.28 ± 0.28	0	4
total	405.6 ± 16.4	293.7 ± 9.1	233.3 ± 7.0	
^{3}He production	93.2 ± 7.9	58.6 ± 4.1	35.7 ± 2.8	
^{3}He (%)	23.0 ± 2.3	19.9 ± 1.4	15.3 ± 1.2	
$\langle n_c \rangle$	3.98 ± 0.21	4.05 ± 0.13	4.06 ± 0.13	

$\bar{p}$–nucleus reaction cross sections for ^{4}He, ^{12}C, ^{20}Ne, ^{27}Al, ^{40}Ca and ^{65}Cu [9,11,12] and obtained for the free parameter R the value 0.94 ± 0.04. This result is in agreement with the value $R \simeq 1$ found by Kondratyuk et al. [13] in the analysis of ($\bar{p}$, ^{2}H) data of ref. [5]. The fit of the 300 MeV/c ^{4}He data from this experiment gives the value R = 0.71 ± 0.07. This value is both in agreement with the result of Dalkarov and Karmanov (R = 0.83) and does fit equally well the ($\bar{p}$, ^{12}C) differential elastic scattering cross section data of ref. [9].

In fig. 2 the charged prong multiplicity distributions at 179.6 MeV, 48.7 MeV and 19.6 MeV are shown. Since at 19.6 MeV only annihilation processes are present, the negative pion multiplicity distribution at this energy can be obtained straightforwardly from table 1. In fact no π^- is produced in one-prong event, only one

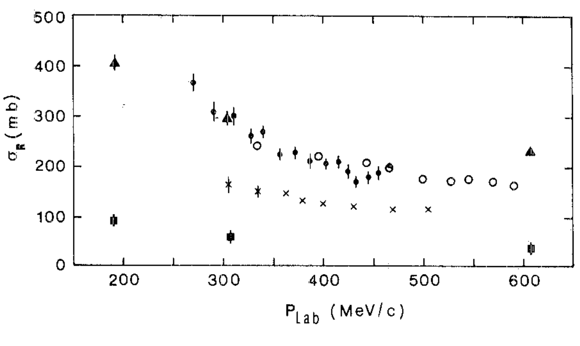

Fig. 1. Reaction cross sections versus $\bar{p}$ momentum. ▲: $\bar{p}^4$He, this experiment (the data include annihilation, inelastic scattering and charge exchange); ▪: $\bar{p}^4\text{He} \to {}^3\text{He}$ + anything, this experiment; ○: $\bar{p}^2$H, ref. [5] (the data include annihilation and charge exchange); •: $\bar{p}^2$H, ref. [6] (the data include annihilation and charge exchange); ×: $\bar{p}$p, ref. [7].

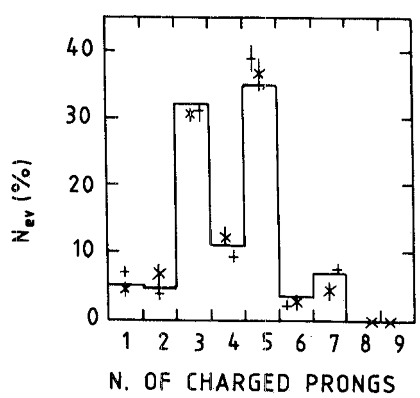

Fig. 2. Charged prong multiplicity distributions. ×: 19.6 MeV (609 events); –: 179.6 MeV (1097 events); the histogram gives the 48.7 MeV distribution (1048 events).

Table 3
Branching ratio (%) for events with different numbers of π^-. ^{2}H data from refs. [5,6]. $\langle n_{\pi^-}\rangle$ is the mean number of π^- per event.

N_{π^-}	BR(^{4}He)			BR(^{2}H)		
	19.6 MeV	48.7 MeV	179.6 MeV	0–39 MeV	57.4 MeV	170.5 MeV
0	4.7 ± 0.9	5.3 ± 0.7	7.0 ± 0.8	3.7 ± 0.2	6.2 ± 0.6	7.1 ± 0.4
1	37.7 ± 2.5	37.5 ± 1.9	35.4 ± 1.8	31.4 ± 0.7	28.7 ± 1.5	26.0 ± 0.9
2	49.7 ± 2.8	46.1 ± 2.1	47.4 ± 2.0	52.3 ± 0.9	52.9 ± 2.2	53.3 ± 1.5
3	7.4 ± 1.1	10.8 ± 1.0	9.9 ± 0.9	12.4 ± 0.4	12.0 ± 2.4	13.4 ± 0.7
4	0.3 ± 0.2	0.3 ± 0.2	0.4 ± 0.3	0.3 ± 0.1	–	–
$\langle n_{\pi^-}\rangle$	1.59 ± 0.07	1.63 ± 0.04	1.61 ± 0.05	1.74 ± 0.03	1.70 ± 0.08	1.73 ± 0.04

π^- may be produced in two- and three-prong events, and so on. The multiplicity distribution at 19.6 MeV and those very similar at the other energies are reported in table 3.

As far as charged prongs production is concerned, the following points can be stressed: (a) the strong predominance of odd-prong events over the even ones: 85% against 15% at 179.6 MeV; 77% against 23% at 19.6 MeV (from table 2); (b) the strict similarity of the behaviours of the multiplicity distributions at all energies (see fig. 2); (c) the fact that the percentages of events with one, two, three prongs are the same, within the experimental errors, at 19.6 MeV (where only annihilation is possible), at 48.7 and at 179.6 MeV (where all inelastic channels are open): 0.425 ± 0.030; 0.422 ± 0.024; 0.425 ± 0.023, respectively.

We can conclude that inelastic processes are less than about 3% and annihilation is by far the dominant mechanism in ($\bar{p}$, ^{4}He) interaction, in agreement with preceding experiments on the ($\bar{p}$, ^{12}C) interaction [9, 14,15]. This is confirmed also by the data on ^{3}He production. ^{3}He nuclei can be produced both by direct $\bar{p}$–neutron annihilation and – above 20 MeV – by the knock-out process. Nevertheless, the cross section and the relative percentage of ^{3}He production decrease in value as the energy increases above threshold, indicating the minor role played by the knock-out process.

The above arguments must hold, of course, for ^{3}H production too. Now from the fit of $\bar{p}$–nucleus reaction cross sections by the standard Glauber theory, we found that at 600 MeV/c the probability for an antiproton to annihilate on a proton (with ^{3}H production) or on a neutron (with ^{3}He production) is almost equal. It follows that, in particular, a rate around 50% can be expected for ^{3}He production. At 300 MeV/c $\sigma_{\bar{p}n}$ turned out to be $\simeq 0.7\ \sigma_{\bar{p}p}$ and hence one assumes $\sigma(^3\mathrm{He}) \simeq 0.7\ \sigma(^3\mathrm{H})$, from which a rate of ^{3}He around 41% can be predicted. These values are in disagreement with the rates deduced in this experiment, which are about 20% (see table 2). Some processes must therefore break ^{3}He nuclei, so as to enrich the odd-prong channels.

If one can ascribe the breaking of ^{3}He nuclei to final state interaction (FSI) only (among annihilation pions and residual nucleons), the percentage of FSI can be evaluated by the formula

$$P_{\mathrm{FSI}} = [\sigma_{\mathrm{R}} - \sigma(^3\mathrm{H}) - \sigma(^3\mathrm{He})]/\sigma_{\mathrm{R}},$$

where σ_{R} is the total reaction cross section. By using the data of table 3 and the above assumptions on $\sigma(^3\mathrm{H})$, one obtains a contribution of FSI ranging from about 70% at 600 MeV/c to about 44% at 300 MeV/c. These values are a factor of 2–3 higher than that deduced in the case of deuterium [16], which might be due to the more bound structure of the ^{4}He nucleus and hence t a higher probability of FSI. A preliminary calculation based on the intranuclear cascade model [17] shows that FSI after annihilation cuts down, at the energies of the experiment, the ^{3}He production to about 20%, in agreement with the present experimental rates.

The role of FSI in the ($\bar{p}$, ^{4}He) interaction is clearly displayed also when the π^- multiplicity distribution is compared with the corresponding one in deuterium, at about the same energies (see table 3). It is in fact remarkable that in ^{4}He the one-π^- channel is more enriched as to ^{2}H, while the higher multiplicity channels show an opposite behaviour. As a consequence, the mean number of π^- per event turns out to be lower in the ^{4}He case. The global result can be ascribed to secondary pion absorption due to FSI with a small multiplicity-dependent effect, which depletes two- and three-π^- channels in favour of one-π^- events.

Different mechanisms, as well, might also be effective in breaking ^{3}He nuclei, such as the formation of an antiproton–nucleus compound system before annihilation, or the annihilation involving more than one nucleon (see, for instance, ref. [18] and references quoted therein). The latter process is expected to produce highly energetic protons and strange particles with a rate higher than that on a free nucleon. At present, our preliminary analysis of V^0 production does not indeed reveal features different from those observed in the case of $\bar{p}$ annihilation on a free proton [19, 20] (at 270 MeV, a production rate of 3% was found).

The measurements of energy and angular distributions of the reaction products, which are in progress, together with Monte Carlo calculations as those reported in refs. [17,21–24] will permit us a better understanding of the many problems raised by the present analysis.

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