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

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ABSTRACT

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 prong and negative pion multiplicities and cross sections for the production of ^3He are given. A comparison with $\bar{p}^2\text{H}$ is performed. The previously obtained 179.6 MeV results are also taken into account.

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In a previous paper (1) we reported some experimental results on the inelastic interaction of 179.6 MeV antiprotons with ${}^4\text{He}$ nuclei. Here we present new results obtained at 19.6 and 48.7 MeV. The total reaction cross section for ${}^3\text{He}$ production, the charged prong and negative pion multiplicities and V^0 production rate have been measured. In the discussion, the previously obtained results are also taken into account.

The research was performed by means of a self-shunted streamer chamber in magnetic field exposed to the antiproton beam of the LEAR facility at CERN. The chamber has a sensitive volume of $(70 \times 90 \times 18) \text{ cm}^3$ and was filled with the target gas at about 970 mbar and 25 °C. Temperature and pressure were measured during each data taking and their relative variations did not exceed a few parts per thousand. The experimental apparatus and its performances were described in detail in Ref. (2). The effective beam energies in the chamber resulted to be 19.6 and 48.7 MeV (192.8 and 306.2 MeV/c). The magnetic field was 0.415 T and 0.630 T, respectively, at the two energies.

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 photograph, a fact which makes very easy the vertex recognition. 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 prongs 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 different scanners in the 96.5% of the cases. In the remaining cases an uncertainty of ± 1 prong - 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.

Nevertheless, considering that in about 1 atm of helium a 1 cm long track may correspond to the range of a 0.25 MeV α -particle (or a 0.16 MeV proton), it is worth emphasizing that this detector allows to get the more accurate determination of charged prong multiplicities at present obtainable.

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

In the fiducial region of the chamber 609 reaction events have been produced by about $1.1 \cdot 10^6$ 19.6 MeV antiprotons; 1048 events by about $2.8 \cdot 10^6$ 48.7 MeV antiprotons and 1097 events by about $3.6 \cdot 10^6$ 179.6 MeV antiprotons.

The possible $(\bar{p}, {}^4\text{He})$ reaction channels are listed in Table I and include: $\bar{p}p$ charge exchange, inelastic scattering (break-up and knock-out), annihilation with emission of pions followed by pion-nucleon interaction. The processes involving strange particles production were not taken into account. Elastic events were checked through coplanarity measurements.

The channels are ordered in accordance with the number of charged prongs and of negative pions. The annihilation reactions are distinguished by the different processes involved.

The total charge of the $(\bar{p}, {}^4\text{He})$ system being odd (+1), it follows that $\bar{p}$ annihilation on one neutron gives rise to reactions with an even number of prongs involving a recoil ${}^3\text{He}$ -particle. Initial and final state interactions can break the ${}^3\text{He}$ 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 ($\bar{p} + {}^4\text{He} \rightarrow \bar{p}pt$) and charge exchange ($\bar{p} + {}^4\text{He} \rightarrow \bar{n}nt$) are,

respectively, 26.6 MeV and 28.1 MeV. Therefore, annihilation is the only inelastic process which takes place at 19.6 MeV, the lowest energy involved in the experiment.

It must be also recalled that the measurement of the production rate of different heavy particles such as ^2H , ^3H , ^3He is of great interest for cosmological theories in order to impose limits on important cosmological parameters (3).

In Table II 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 section; 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 $(\bar{p}, ^4\text{He})$ reaction cross section is compared in Fig. 1 with the reaction cross section values for hydrogen and deuterium. It is interesting to note that, as the $\bar{p}$ energy decreases, the reaction cross section increases in deuterium more rapidly than in hydrogen and in ^4He ; at 300 MeV/c the $(\bar{p}, ^4\text{He})$ and $(\bar{p}, ^2\text{H})$ cross sections have about the same value. Moreover, the similar energy behaviour of $(\bar{p}, ^4\text{He})$ reaction cross section and $(\bar{p}, p)$ cross section does suggest the hypothesis that $\bar{p}$ annihilation on a quasi-free nucleon is the main mechanism of $(\bar{p}, ^4\text{He})$ interaction (see also below).

It is also possible to obtain interesting informations on the annihilation ratio $R = \sigma_{\bar{p}n}^- / \sigma_{\bar{p}p}^-$. Dalkarov and Karmanov showed (7) that the 300 MeV/c $(\bar{p}, ^{12}\text{C})$ elastic scattering data (8) can be described surprisingly well by the Glauber approximation (9). With the same approach, by using the standard Glauber theory, we fitted the 600

MeV/c $\bar{p}$ -nucleus reaction cross sections for ^4He , ^{12}C , ^{20}Ne , ^{27}Al , ^{40}Ca and ^{65}Cu (8,10,11) and obtained for the free parameter R the value 0.94 ± 0.04 . This result is in agreement with the value $R \approx 1$ found by Kondratyuk et al. (12) in the analysis of ($\bar{p}$, ^2H) data of Ref. (4).

The fit of the 300 MeV/c ^4He data from this experiment gives the value $R = 0.71 \pm 0.07$. This value is both in agreement with the result of Dalkarov and Karmanov ($R = 0.83$) and does fit as much well the ($\bar{p}$, ^{12}C) differential elastic scattering cross section data of Ref. (8).

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 I. In fact no π^- is produced in one-prong event, only one π^- may be produced in 2- and 3-prong events, and so on. The multiplicity distribution at 19.6 MeV is reported in Table III, together with the distributions measured at the other experimental energies.

As far as charged prong 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 II);
- 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 1, 2, 3 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.

The conclusion that can be drawn is that inelastic processes play a minor role in ($\bar{p}$, ^4He) interaction, since they are less than about 3%. This point is in agreement with the recent results of Garreta et al. (8) in $\bar{p}$ scattering on ^{12}C at 300 and 600 MeV/c ($\sim 1\%$); with those of Nakamura et al. (13) in $\bar{p}$ charge-exchange reaction on ^{12}C at 590 MeV/c ($\sim 2\%$); and with those of Thompson et al. (14) in $\bar{p}$ knock-out reaction on ^{12}C at 1.73 GeV ($\sim 5\%$). Therefore annihilation is by far the dominant mechanism in ($\bar{p}$, ^4He) interaction.

As regards ^3He production, ^3He -nuclei can be produced by direct $\bar{p}$ -neutron annihilation and - above 20 MeV - by knock-out process. The minor role played by the latter is confirmed by the fact that both the cross section and the relative percentage of ^3He production decrease in value as the energy increases above threshold. In particular, the decreasing of the 2-prong events, which include the ^3He production by knock-out, is equal to $(36 \pm 9)\%$ about the same value, within the errors, of that for 4- and 6-prong events $(39 \pm 5)\%$ where only annihilation is present.

The above arguments must hold, of course, for ^3H 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 ^3H production) or on a neutron (with ^3He production) is almost equal. It follows that, in particular, a rate around 50% can be expected for ^3He production. At 300 MeV/c it turned out $\sigma_{\bar{p}n} \simeq 0.7 \sigma_{\bar{p}p}$ and hence one assume $\sigma(^3\text{He}) \simeq 0.7\sigma(^3\text{H})$, from which a rate of ^3He around 41% can be predicted. These values are in disagreement with the rates deduced in this experiment, which are about 20% (see Table II). Some processes must therefore break ^3He -nuclei, so as to enrich the odd-prong channels.

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

evaluated by the formula

$$P_{\text{FSI}} = \left[\sigma_R - \sigma(^3\text{H}) - \sigma(^3\text{He}) \right] / \sigma_R \quad \text{where } \sigma_R \text{ is}$$

the total reaction cross section. By using the data of Table II and the above assumptions on $\sigma(^3\text{H})$, one obtains a per cent 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 (15), which might be due to the more bound structure of ^4He -nucleus and hence to a higher probability of FSI. A preliminary calculation based on the intranuclear cascade model (16) shows that FSI after annihilation cuts down, at the energies of the experiment, ^3He production to about 20%, in agreement with the present experimental rates.

Different mechanisms, as well, might also be effective in breaking ^3He -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. (17) and references herein quoted). The latter process is expected to produce highly energetic protons and a strange particles production 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 (18,19) (at 270 MeV, a production rate of 3% was found).

The role of FSI in $(\bar{p}, ^4\text{He})$ 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 III). It is in fact remarkable that in ^4He the one- π^- channel is more enriched as to ^2H , 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 ^4He case. The global result can be ascribed to secondary pion absorption due to FSI with a small multiplicity-dependent effect, which depletes 2-

and $3-\pi^-$ channels in favour of one- π^- events.

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. (16, 20, 21, 22 and 23) will permit us a better understanding of the many problems raised by the present analysis.

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FIGURE CAPTIONS

FIG. 1 - Reaction cross sections vs. $\bar{p}$ momentum: $\blacktriangle\bar{p}^4\text{He}$: this experiment (the data include annihilation, inelastic scattering and charge exchange); $\blacksquare$) $\bar{p}^4\text{He} \rightarrow {}^3\text{He} +$ anything: this experiment; $\circ$) $\bar{p}^2\text{H}$: Ref. (4) (the data include annihilation and charge exchange); $\bullet$) $\bar{p}^2\text{H}$: Ref. (5) (the data include annihilation and charge exchange); $\times$) $\bar{p}\text{p}$: Ref. (6).

FIG. 2 - Charged prong multiplicity distributions: $\times$) 19.6 MeV; $\circ$) 48.7 MeV; $-$) 179.6 MeV.

TABLE CAPTIONS

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

TABLE II - Total reaction cross section, cross section for reactions with different numbers of charged prongs and for ${}^3\text{He}$ production. All quantities are in mbarn. $\langle n_c \rangle$ is the mean number of charged prongs per event.

TABLE III - Branching ratio (%) for events with different numbers of π^- . ${}^2\text{H}$ data from Refs. (4,5). $\langle n_{\pi^-} \rangle$ is the mean number of π^- per event.

TABLE I

Number of charged prongs	$(\bar{p}, {}^4\text{He})$ reaction products	Reaction type	n. of 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	$3n+\pi^++M\pi^0$	annihilation + ch.exch.	0
2	$\bar{p}+{}^4\text{He}$	elastic scattering	0
2	$\bar{p}+{}^3\text{He}+n$	knock-out	0
2	${}^3\text{He}+\pi^-+M\pi^0$	$\bar{p}n$ annihilation	1
3	$\bar{p}+2X+Nn$	break-up	0
3	$\bar{p}+t+p$	knock-out	0
3	$2X+\pi^-+Nn+M\pi^0$	annihilation	1
3	$t+2\pi^++M\pi^0$	$\bar{p}p$ annihilation	1
3	$X+2\pi^++Nn+M\pi^0$	annihilation	1
3	$3\pi^++3n+M\pi^0$	annihilation + ch.exch.	1
4	${}^3\text{He}+3\pi^++M\pi^0$	$\bar{p}n$ annihilation	2
5	$2X+3\pi^++Nn+M\pi^0$	annihilation	2
5	$t+4\pi^++M\pi^0$	$\bar{p}p$ annihilation	2
5	$X+4\pi^++Nn+M\pi^0$	annihilation	2
5	$5\pi^++3n+M\pi^0$	annihilation + ch.exch.	2
5	$3X+2\pi^-+M\pi^0$	annihilation + ch. exch.	2
6	${}^3\text{He}+5\pi^++M\pi^0$	$\bar{p}n$ annihilation	3
7	$2X+5\pi^++Nn+M\pi^0$	annihilation	3
7	$t+6\pi^++M\pi^0$	$\bar{p}p$ annihilation	3
7	$X+6\pi^++Nn+M\pi^0$	annihilation	3
7	$7\pi^++3n+M\pi^0$	annihilation + ch. exch.	3
7	$3X+4\pi^++M\pi^0$	annihilation + ch. exch.	3
8	${}^3\text{He}+7\pi^++M\pi^0$	$\bar{p}n$ annihilation	4
$X = p, d \quad 0 \leq N \leq 2 \quad M \geq 0$			

TABLE II

Number of charged prongs	19.6 MeV	48.7 MeV	179.6 MeV	n. of π^-
1	19.30 ± 3.5	15.7 ± 2.1	16.4 ± 1.9	0
2	27.3 ± 4.2	15.4 ± 4.2	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	10.4 ± 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	297.7 ± 9.1	233.3 ± 7.0	
$^3\text{He prod.}$	93.2 ± 7.9	58.6 ± 4.0	35.7 ± 2.8	
$^3\text{He } \%$	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	

TABLE III

^4He				^2H		
N_{π^-}	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

FIG. 1

FIG. 2