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ANNIHILATION OF ANTIPROTONS AT REST IN ^3He AND ^4He .

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Summary. - At LEAR of CERN the annihilation of antiprotons, stopping in ^3He and ^4He filling a self shunted streamer chamber in a magnetic field, has been studied. The charged particle multiplicities have been measured and the relative probabilities of π^- production in $\bar{p}^3\text{He}$ and $\bar{p}^4\text{He}$ annihilation events have been obtained. The ratio between the $\bar{p}$ annihilation probability on the neutron and the proton for ^3He and ^4He has been deduced to be about half the value obtained for ^2H in bubble chamber experiments. The analyses of the results shows that this difference cannot be due only

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to the pion final state interaction or to the shadow effect of the nucleons of the nuclei. The probability of $\bar{p}$ annihilation at rest on a proton bound in the nucleus results to be twice as high as that on a bound neutron, showing the dominance of annihilation in the $I=0$ isospin states.

1. Introduction.

One of the most important problems of the low energy antiproton physics is the determination of the amplitude of the elementary antinucleon-nucleon interaction, in particular, the study of $\bar{N}N$ interaction in different isospin states. For this, experimental information on scattering and annihilation of $\bar{p}$ on the proton and on the neutron is necessary. Up to now, the $\bar{n}p$ interaction has been poorly studied because of the lack of antineutron beams with characteristics comparable with those of the new $\bar{p}$ beams. For this reason the results of the study of $\bar{p}$ interaction with very light nuclei, such as ^2H , ^3He , ^4He , are particularly important, owing to the possibility to extract information on the $\bar{p}n$ scattering amplitude.

The annihilation of antiprotons on ^4He has been studied at 20, 50 and 180 MeV, and also at rest ^{1,2)}. It has been deduced that the ratio $R = W_n^{\text{ann}} / W_p^{\text{ann}}$, between the probability of $\bar{p}$ annihilation on a neutron and on a proton bound in ^4He nucleus, in the whole energy interval taken into consideration, is lower than unity. At rest the R value results to be (0.42 ± 0.05) , about half the corresponding R value deduced studying the $\bar{p}^2\text{H}$ annihilation in bubble chamber experiments, that is $R = (0.82 \pm 0.03)$ and (0.75 ± 0.02) in ref.3 and 4, respectively.

The different values between ^2H and ^4He could be due to several reasons. In the bubble chamber experiments^{3,4)} the $\bar{p}$ capture occurs in the S-state for owing to the strong Stark effect⁵⁾. In our experiment with gaseous targets at atmospheric pressure, the $\bar{p}$ capture occurs from P- and D-levels. Moreover, in the bubble chamber experiments the $\bar{p}$ with momenta lower than about 300 MeV/c were considered at rest, while in our case the $\bar{p}$ in 75% of the events have less than 10 MeV/c and the rest have less than 50 MeV/c. At LEAR, the momentum resolution of our incoming beam was $\Delta p/p < 10^{-3}$, so that also due to the low density target, it was possible to determine with high precision the zone of annihilation. On the other hand, nontrivial physical effects could also cause the low R values. For example, the $\bar{p}n$ interaction occurs in the pure isospin state $I=1$, but in the $\bar{p}p$ interaction there are contributions from amplitudes with $I=1$ and $I=0$, so that for free nucleons one expects:

$$R = \frac{W_n^{\text{ann}}}{W_p^{\text{ann}}} = \frac{2W(I=1)}{W(I=0)+W(I=1)} \quad (1)$$

The low values of R, deduced in the ^4He experiment²⁾, show an anomalous high interaction in the $I=0$ state ($W(I=0)/W(I=1)=3.76$) which may be explained, for example, by resonances in $\bar{N}N$ systems, not excluded near the threshold⁶⁾. Moreover, it is known that in the vicinity of the threshold of $\bar{p}p$ interaction some strange oscillations⁷⁾ of the ratio $\rho = \text{Re } f(0)/\text{Im } f(0)$ are observed. Bearing in mind the importance of this problem, we have made an attempt to determine R for the ^3He nucleus in a way differing from the one adopted in ref.2, and also for the ^4He nucleus utilizing a different part of our experimental data.

2. Experimental method.

The experimental apparatus has been described previously in detail⁸⁾, here we only recall the chief features. The self shunted streamer chamber, filled with ^3He or ^4He at 1 atm, serves at the same time as a target and detector⁹⁾. The volume of the chamber was $70 \times 90 \times 18 \text{ cm}^3$ and the magnetic field was 0.22 T. The thickness of the target was $\sim 15 \text{ mg/cm}^2$. The trigger for the high voltage pulse generator of the chamber was provided by a hodoscope of thin scintillation counters⁸⁾ placed along the beam, in front of the chamber. Taking into account the energy losses through the beryllium end wall of the vacuum line of LEAR, the scintillation counters of the trigger and through the entrance window of the chamber, the $\bar{p}$ kinetic energy was $\sim 2.5 \text{ MeV}$ and the diameter of the beam was about 2 cm. The $\bar{p}$ stop points took place about the center of the chamber; in Fig. 1 the distribution of the annihilation events along the chamber is shown, the distances are from the entrance window. A clear peak is seen and its position coincides with the calculation value, while its width is mainly determined by the natural straggling of the antiprotons in the detectors and in the walls along the beam line and secondly by the annihilation probability in flight at very low energy. The events were photographed by two cameras, with about one event per photo. Each film has been scanned three times and the efficiency of finding the interaction events was 99.5%.

3. Antiproton annihilation on ^3He .

For achieving well localized bright tracks in the chamber 0.14% of $\text{C}_{4,10}\text{H}_{10}$ was included⁹⁾ in the ^3He gas filling of the chamber. Only the events with vertices occurring within the 25 cm long central region in the chamber were taken into account. Inside this fiducial region 3127 annihilations have been found.

Since the total charge of the final state in $\bar{p}^3\text{He}$ annihilation equals +1, the charge prong multiplicity distribution contains only odd prong events as it is shown in Table I. Nevertheless, we observed also about 1.6% of even prong events, which are due to annihilations on C_4H_{10} admixture or to the fact that some very short tracks are undetected. We estimated that the events due to annihilation on the admixture to make up for about 2.4% of the total number of events, which agrees with the above 1.6%. We made no corrections for the contribution of those spurious events to the odd prong events, consequently the systematic error in the multiplicity measurements is of about 2%.

For analysis of antiproton annihilation in ^4He , 1009 events inside the fiducial volume were obtained. The films we analyzed have been obtained after those used for the statistics presented in ref.2, so that these two different statistical samples may be summed up. The corresponding charged prong multiplicity distribution is given in Table II.

The admixtures present in the ^4He gas filling of the chamber were $\sim 0.1\%$. In ^4He we estimated the amount of events in which a track can be lost to be $\sim 0.1\%$ of the total number of events and neglected such cases.

It must be stressed that a streamer chamber operating at low pressure represents a very good instrument for studying charged particle multiplicities. In fact, for instance, the tracks of a 250 keV α -particle or of a 160 keV proton are 1 cm long in the chamber and are quite visible. In contrast, the tracks of spectator protons in $\bar{p}d$ -annihilation events registered in a bubble chamber¹⁰⁾ were not detected in 73% of the events.

4. Estimation of R_O .

The relative probabilities of different annihilation channels

involving different charged particle multiplicities may be conveniently compared, for differing nuclei, by comparing the number of negative pions produced. It is readily shown that in the case of annihilation on ${}^3\text{He}$ $N_{\pi^-} = (N_{\text{ch}} - 1)/2$, while in the case of $\bar{p}$ ${}^4\text{He}$ annihilation the charged prong multiplicities $N_{\text{ch}} = 1, 2, 3, 4, 5, 6, 7, \dots$ correspond, respectively, to events with $N_{\pi^-} = 0, 1, 2, 3, \dots$. In Table III are presented the relative probabilities, B_A^i , of negative pion production in annihilation of stopping antiprotons on the ${}^3\text{He}$ and ${}^4\text{He}$ nuclei, and on ${}^2\text{H}$ (from ref.3). One can see that, although the values of B_A^i for the different isotopes of helium differ little, they differ quite noticeably from the corresponding quantities for $\bar{p}d$ -annihilation.

The relative probabilities B_A^i can be computed knowing the outputs b_p^i and b_n^i of negative pions in $\bar{p}p$ - and $\bar{p}n$ -annihilation, respectively, as well as the ratio from R from (1):

$$B_A^i = W_p^{\text{ann}} \cdot b_p^i + W_n^{\text{ann}} \cdot b_n^i \quad (2)$$

Here W_p^{ann} and W_n^{ann} represent the annihilation probabilities on the proton and the neutron, respectively, bound in the nucleus; i is the negative pions multiplicity if one assumes the annihilation probability on the proton or on the neutron in the nucleus to depend only on their number and on the ratio R_0 for free nucleons, then:

$$W_p^{\text{ann}} = \frac{Z}{Z + NR_0} ; \quad W_n^{\text{ann}} = \frac{NR_0}{Z + NR_0} \quad (3)$$

where Z and N , respectively, are the number of protons and neutrons in the nucleus, and R_0 represents the ratio between the annihilation probabilities on the neutron and on the proton in the case of free nucleons. It is readily seen that, when $Z=N$, R equals R_0 .

In Table III the calculated values are given of B_A for $\bar{p}{}^2\text{H}$ anni-

hilation. The relative outputs b_p^i for $\bar{p}p$ annihilation are from ref.¹¹⁾ with account of kaon production in the final state. The relative outputs b_n^i are taken from ref.¹²⁾. The R_0 value has been chosen to be 0.8, as found in ref.3 and 4 and in agreement with the value of $\bar{n}p$ and $\bar{p}p$ annihilation cross section ratio deducible at low energy from the data of ref.13 and 7, respectively. One can see that the multiplicity distribution for negative pions produced in $\bar{p}d$ annihilation is described well by relations (2)-(3) which do not take into account the pion final state interaction. However, from (3) it follows that for a given R_0 the multiplicity distributions for any nuclei with $Z=N$ should be identical. Actually, this is not so, which is confirmed by the results for annihilation in ^4He presented in Table III.

A possible explanation of the above discrepancy is that the pions produced in annihilation may undergo interaction in the final state with the nucleons of the residual nucleus and, thus, alter the relative probabilities B_A^i . In annihilation an average of 5 pions is created with a mean energy of $T \sim 220$ MeV. Such pions may quite effectively interact with the residual nucleus. However, not any final-state interaction (FSI) will lead to an alteration of the spectrum, B_A^i . A change in the number of negative pions will only take place owing to reactions of the charge-exchange type:

or to pion absorption as:

Processes (4) and (6) lead to the loss of one negative annihilation pion, while reaction (5) results in the production of an additional negative pion. The pion absorption channel, for the light nuclei as ${}^2\text{H}$, ${}^3\text{He}$ and ${}^4\text{He}$, is less important¹⁴⁾ than the charge exchange. Thus, variation of the negative pion multiplicity distribution is due to two processes counteracting each other.

In Figs. 2,3 the relative probabilities B_A^i are presented for annihilation of antiprotons in ${}^3\text{He}$ and ${}^4\text{He}$ computed with account of FSI. The probability for a pion to undergo interaction in the final state with a nucleon of the residual nucleus was taken¹⁵⁾ to be $W_{\text{FSI}}=0.2$, while the probability of losing a negative pion through charge exchange in the final state was assumed to be $W_{\text{CEX}}=0.2$ (approximately equal¹⁵⁾ to the ratio of the cross section of reaction (4) to the total $\pi^{-}p$ -interaction cross section in the Δ_{33} -resonance region). The probability for the FSI to result in the production of an additional negative pion was considered equal to W_{CEX} . In calculations the relative probability of each exclusive $\bar{p}p$ and $\bar{p}n$ annihilation channel, in which a given number of negative and neutral pions is produced, was taken into account, as well as the fact that the loss of a negative pion in the i -th $\bar{p}A$ annihilation channel led to the appearance of an additional event in the $(i-1)$ -th bin of the multiplicity distribution. The results of calculations for different R_0 are represented by solid lines in the plots of Figs.2 and 3. One can see that taking into account the FSI does not alter the multiplicity distribution significantly, but the general agreement with the ex-

perimental data does becomes better.

It must be stressed that, although taking into account the FSI on the whole, leads to small changes in the probabilities B_A^i , charge exchange processes are, nevertheless, themselves quite significant (see Table IV) and occur in a great part (10-20%) of the annihilation events.

When the quantities R_O and W_{FSI} are treated as free parameters, the best agreement with experimental data is obtained with the following values:

$$\begin{aligned} R_O &= (0.35 \pm 0.07), \quad W_{FSI} = (0.15 \pm 0.03) \text{ for } {}^3\text{He}, \\ R_O &= (0.48 \pm 0.10), \quad W_{FSI} = (0.08 \pm 0.05) \text{ for } {}^4\text{He}. \end{aligned} \quad (7)$$

The R_O value deduced for the ${}^4\text{He}$ nucleus is in good agreement with the previous result, $R = (0.42 \pm 0.05)$, of ref.²⁾.

6. Discussion of the results.

The R_O value obtained from $\bar{p}^2\text{H}$ data^{3,4)} results two times higher than the values obtained from $\bar{p}^3,4\text{He}$ data; tentatively the disagreement could be explained by the too much simplified relation (3) between the $\bar{p}$ annihilation probability on bound nucleons W_n and W_p and the corresponding probabilities for free nucleons. It may turn out that the relation between R_O and W_n, W_p changes significantly owing to the screening of nucleons in the nucleus. Let us estimate the shadow effect utilizing simple semi-classical arguments, such

as the ones made use of by Glauber in ref.¹⁶⁾. Let δ_{pn} be the probability for the proton happen to be in the shadow of a neutron; then

$$\delta_{pn} = \frac{f_n}{4\pi r_{NN}^2}, \quad (8)$$

where f_n is the annihilation probability on a free neutron, which is determined solely by the effective dimensions of the neutron $f_n = \pi r_{ann}^2$, where r_{ann} is the effective annihilation radius. The quantity r_{NN} occurring in (8) is the mean distance between the nucleons in the nucleus. Then, it is not difficult, for instance, for ${}^4\text{He}$ annihilation, to write out the probabilities W_p and W_n with account of the shadow effect of the nucleons:

$$\begin{aligned} W_p &= 2f_p(1 - \delta_{pp} - 2\delta_{pn}), \\ W_n &= 2f_n(1 - \delta_{nn} - 2\delta_{np}), \end{aligned} \quad (9)$$

where δ_{pp} , δ_{nn} and δ_{np} correspond to screening corrections in the pp, nn and np systems, which are determined as in (8). Then making use of (8) and (9) and taking into account that $f_n/f_p = R_o$, one can obtain the following relationship between R and R_o :

$$R = R_o \frac{1 - \frac{1}{4} (r_{ann}/r_{NN})^2 (R_o + 2)}{1 - \frac{1}{4} (r_{ann}/r_{NN})^2 (1 + 2R_o)}. \quad (10)$$

The screening is most significant, when $r_{ann} = r_{NN}$. In this case, if $R_o = 0.8$ is substituted into (11), we obtain $R = 0.69$, which is no-

ticeably larger than the experimentally observed values (7). If, which is more probable, the effective annihilation radius is smaller than the average distance between the nucleons in the nucleus, for example, $r_{\text{ann}} = r_{\text{NN}}/2$, then from (10), under the same assumption that $R_0 = 0.8$, it follows that $R = 0.79$. Thus, the shadow effect is very small.

7. Conclusion.

We measured the production probability of different numbers of charged particles in the annihilation of stopping antiprotons in ^3He and ^4He . It has been found that the multiplicity distributions differ quite significantly from the corresponding distributions for $\bar{p}^2\text{H}$ annihilation. Analysis of the obtained results has revealed that the said difference cannot be due only to interaction in the final state of the annihilation pions or to shadow effects of nucleons in the nucleus. It was obtained that the annihilation probability on a proton in the nucleus is approximately twice as high as the probability of annihilation on a neutron. This fact points to a significant domination of annihilation in the state with isospin $I=0$, near the threshold.

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Table I. Relative probabilities B_A of $\bar{p}^3\text{He}$ annihilation channels with differing charged particle multiplicities.

N_{ch} (prongs)	N_{ev} (events)	B_A (%)
1	150	4.8 ± 0.4
3	1217	38.9 ± 0.8
5	1465	46.9 ± 0.9
7	275	8.8 ± 0.5
9	18	0.6 ± 0.1
Total	3125	

Table II. Relative probabilities B_A of $\bar{p}^4\text{He}$ annihilation channels with differing charged particle multiplicities.

N_{ch} (prongs)	N_{ev} (events)	B_A (%)
1	28	2.8 ± 0.5
2	57	5.7 ± 0.7
3	320	31.6 ± 1.5
4	123	12.2 ± 1.0
5	354	35.1 ± 1.5
6	42	4.2 ± 0.6
7	76	7.5 ± 0.8
8	3	0.3 ± 0.2
9	3	0.3 ± 0.2
10	2	0.2 ± 0.1
11	1	0.1 ± 0.1
Total	1009	

Table III. Relative probability B_A^i of π^- production in antiproton annihilation on ${}^2\text{H}$, ${}^3\text{He}$, ${}^4\text{He}$, at rest.

Nucleus	$\langle N_{\pi^-} \rangle$	π^- multiplicities, $i=0,1,2,3,4$.					
		0	1	2	3	4	
${}^2\text{H}$	1.77	2.9 ± 0.3	30.7 ± 0.9	52.1 ± 1.4	14.1 ± 0.8	—	ref.3
${}^2\text{H}$	—	2.9	31.7	52.6	12.5	0.2	theoretical estimation
${}^3\text{He}$	1.61	4.8 ± 0.4	38.9 ± 0.8	46.9 ± 0.9	8.8 ± 0.5	0.6 ± 0.1	
${}^4\text{He}$	1.69	2.8 ± 0.5	37.3 ± 1.7	47.3 ± 1.8	11.7 ± 1.0	0.6 ± 0.2	

Table IV. Influence of pion interaction in the final state on the relative probabilities B_A^i .

$R_O=0.8, W_{FSI}=0.2, W_{CEX}=0.2$					$W_{FSI}=0.4, W_{CEX}=0.2$		
N_{π^-} (i)	$B_A(\%)$ without account of FSI	$\Delta B_A(\%)$ due to $\pi^0 \rightarrow \pi^-$	$B_A(\%)$ due to $\pi^0 \rightarrow \pi^-$	$B_A(\%)$ with account of FSI	$\Delta B_A(\%)$ due to $\pi^0 \rightarrow \pi^-$	$\Delta B_A(\%)$ due to $\pi^0 \rightarrow \pi^-$	$B_A(\%)$ with account of FSI
0	2.9	-0.3	+1.5	4.1	-0.4	+2.7	5.1
1	31.7	-3.1	+4.4	32.4	-4.9	+7.4	32.5
2	52.6	-3.4	+1.4	49.4	-5.8	+2.2	46.5
3	12.5	-0.5	+0.02	14.0	-0.9	+0.03	15.2

Figure captions.

Fig.1 - Distribution of the $\bar{p}$ ^3He annihilation event vertices along the streamer chamber. The distances are from the entrance window.

Fig.2 - Relative probability B_A^i of $\bar{p}$ annihilation at rest on ^3He with production of $i=0,1,2,3$ negative pions as function of R_O , compared with the behaviours deduced taking into account FSI (full lines) and without FSI (dashed lines). The hatched bands show the errors of the experimental data.

Fig.3 - Relative probability B_A^i of $\bar{p}$ annihilation at rest on ^4He with production of $i=0,1,2,3$ negative pions as function of R_O , compared with the behaviours deduced taking into account (full lines) and without FSI (dashed lines). The hatched bands show the errors of the experimental data.

FIG.1

FIG.2

FIG.3