Nuclear Interactions of Antiprotons with Aluminium and Carbon

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Dedicated to Professor Dr. W. GENTNER *on the occasion of his 60th birthday*

The reactions leading to the production of ^{11}C from ^{12}C and ^{27}Al, and of ^{18}F from ^{27}Al were studied with antiprotons and negative pions of momentum (2.5 – 3.0) GeV/c. No significant differences were found in the cross-section ratios. The experimental uncertainties are in the order of 25%.

The development of high-energy accelerators is providing increasingly intense beams of several particles. In particular, the recent availability of negative pions and antiprotons at CERN has made it possible to study their interactions with complex nuclei.

At present there exist three ways of investigating the interactions of particles such as antiprotons with complex nuclei. We refer to

a) transmission experiments which measure the total interaction cross-section [1];
b) emulsion experiments which give evidence about the "fast cascade" process in the nuclei found in nuclear emulsions [2];
c) nuclear chemistry experiments, which measure the yields of residual nuclei.

For ordinary protons as incident particles, this last method has given very detailed information on the distribution of the final products of the interaction. One important result of these investigations has been that production cross-sections for practically all residual nuclei are virtually independent of the energy of the incoming proton when this is more than about 2 GeV [3].

From this one infers that the "fast cascade" initiated by the incoming proton gives a distribution of excitation energies deposited in the nucleus which is also independent of the proton energy when this is above 2 GeV.

Very little is known about the yield distribution of product nuclei for initiating particles other than protons. REEDER and MARKOWITZ [4] studied some simple reactions of pions on ^{12}C, and RUDSTAM [5] and REMSBERG [6] some simple pion reactions with Cu. Only POSKANZER and REMSBERG [7] have published results on more complex reactions with pions. They studied the production of ^{11}C and ^{18}F from aluminium targets, but could not find any difference between the cross-sections for pion and proton-induced reactions above 1 GeV. An interpretation of this result might be that as the proton-nucleon and pion-nucleon cross-sections are nearly the same for all kinds of interaction (scattering, pion production) it is to be expected that the same distribution of excitation energy will occur for both particles. The yields of final products must then be the same.

In the case of antiprotons, however, the existence of the antiproton-nucleon annihilation process increases the antiproton-nucleon total cross-section to about twice that of the proton-nucleon cross-section (at, say, 2 GeV/c). Antiproton-nucleon annihilation can lead to the formation, within one and the same nucleus, of about five pions. Reabsorption of some or all of these provides a new mechanism whereby a greatly increased amount of energy may be deposited. The magnitude of the increased energy may not by itself be such an important effect as that it could be widely distributed over several nucleons simultane-

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1 B. CORK et al., Phys. Rev. **107**, 248 [1957].
2 U. AMALDI et al., Nuovo Cim. **16**, 977 [1959].
3 See, for example: G. FRIEDLANDER, Proc. Int. Symp. on the Physics and Chemistry of Fission, Vol. **II**, 265 [1965], published by the IAEA, Wien.
4 P. L. REEDER and S. S. MARKOWITZ, Phys. Rev. **133**, B 639 [1964].
5 G. RUDSTAM, Nucl. Phys. **56**, 593 [1964].
6 L. P. REMSBERG, Phys. Rev. **138**, B 572 [1965].
7 A. M. POSKANZER and L. P. REMSBERG, Phys. Rev. **134**, B 779 [1964].

ously. On this crude semiquantitative basis one would expect a progressively greater effect on the formation cross-sections of products which are further displaced from the target. In the present experiments we found it convenient for practical reasons to compare effects due to antiprotons with those due to negative pions.

It is an unfortunate fact that available beams of antiprotons are still of such low intensity that only rather simple reactions can be studied easily. Clearly the effects mentioned in the previous paragraph should be most marked in large target nuclei, but their measurement would be difficult because of the low activity level of each of the many product nuclei. In the hope that the effects might still be observable in a nucleus as small as ^{27}Al, we have so far used only this element as target. The production of ^{11}C and ^{18}F can very easily be measured by means of their positron-annihilation radiation without the use of chemical treatment. This also means, of course, that there are no losses of product activity by the time-delay necessary for chemical processing or failure to achieve 100% efficiency in preparation of the product.

Another difficulty in this kind of experiment is that of assessing the flux of bombarding particles, which has to be known before calculations of absolute cross-sections can be made. In the case of antiprotons we have only rough indications of the flux (see Section 1, Experimental Data) so that conclusions based on absolute cross-section measurements are rather unreliable. However, relative cross-section measurements avoid this factor. Such a one is the ratio of ^{11}C production in carbon targets to that in aluminium targets [written $\sigma_{^{27}\mathrm{Al}}(^{11}\mathrm{C})/\sigma_{^{12}\mathrm{C}}(^{11}\mathrm{C})$]. Here the target would be a sandwich of carbon (or a carbon compound) and aluminium arranged so that both elements are bombarded by the same flux of particles: it does not matter if the pion flux is different from the antiproton flux.

We would expect the above ratio to be bigger for a pure antiproton bombardment than for pion bombardment because the pion reabsorption process should be more important in the $^{27}\mathrm{Al} \rightarrow {}^{11}\mathrm{C}$ reaction than in the $^{12}\mathrm{C} \rightarrow {}^{11}\mathrm{C}$. The second cross-section ratio we have measured is denoted by $\sigma_{\mathrm{Al}}(^{11}\mathrm{C})/\sigma_{\mathrm{Al}}(^{18}\mathrm{F})$ which should be larger for antiprotons than for pions for a similar reason.

1. Experimental Procedures

General considerations

Obviously the success of the experiment depends most critically upon the quality of the antiproton beam, which should be well focused on the target and as free as possible from contamination with other particles. Antiprotons with a large range of momenta are produced when the internally circulating protons in the CERN Proton Synchrotron strike an internal target. They are separated from other particles and a narrow momentum range is selected by a complex sequence of focusing magnets, bending magnets, and electrostatic fields [8]. From the practical point of view it was found that the most suitable place for irradiation was in the beams designated o_2 and o_8 (which are normally used for the 152 cm British National Hydrogen Bubble Chamber and the CERN 2 m Hydrogen Bubble Chamber) near the final mass-slit in front of the chambers themselves.

The distance from the PS itself is more than 100 metres and the general background radiation is small. The exact cross-section of the beam could be determined with a beam intensifying camera [9] (see Fig. 1 *). Here contamination of the beam by π^- and μ^- was negligibly small in two of the runs, but there was a 20% contamination by π^- in the third (see Table 1).

The choice of antiproton momentum to be used in the experiment is determined, in principle, by two factors. The first of these is that the total $(\bar{\mathrm{p}}, \mathrm{N})$ cross-section decreases with increasing $\bar{\mathrm{p}}$ momentum [10] so that one would like to work at the lowest possible momentum. The second is that the $\bar{\mathrm{p}}$ beam intensity available has a rather flat maximum between 2 and 4 GeV/c [11].

Accordingly it would have been preferable to work always at 2 GeV/c. To save time, however, it was decided to use the beam whenever it was currently in use for other experiments when the momentum was in the range (2.5 – 3.0) GeV/c (see Table 1). At our irradiation site the momentum definition was about ±2%.

As already explained, it was not our intention to obtain accurate absolute cross-sections, which would have necessitated the spending of much time in installing and testing a counter telescope immediately behind our target. However, in the last experiment two scintillation detectors operating in coincidence were already positioned some 10 metres downstream and these were used to give an approximate value of the beam intensity. As is shown later, absolute cross-sections based on flux measurements with these counters are in fair

[8] E. Keil and W. W. Neale, Proc. Int. Conf. on High-Energy Accelerators, Dubna (1963), p. 1008.

[9] L. Marshall and A. Wattenberg, Rev. Sci. Instr. **32**, 1258 [1961].

* Fig. 1 on page 1044 a.

[10] U. Amaldi et al., Nuovo Cim. **34**, 825 [1964].

[11] D. Dekkers et al., Phys. Rev. **137**, B 962 [1965].

Irradiation number	Date	Beam information					Target thickness		Counters			
									β^+-annihilation counter (two NaI crystals)			Plastic scintillator
		Momentum of particles	Estimated flux of $\bar{p}$	Contamination of $\bar{p}$ flux	Percentage of flux in the target *	Target area	Plastic scintillator	Aluminium	Size	Background	Counting efficiency	Background
		GeV/c	$\times 10^4$ $\bar{p}$/min			cm^2	cm	cm	(inch)	cpm	%	cpm
5	9–11 Sept. 1964	3.0	3.5 ± 0.4	11% μ^- < 1% π^-	66 ± 3	2×3	1.0	1.0	2×2	0.3	—	33
6	9 Feb. 1965	3.0	2.2 ± 0.5	~20% π^- **	44 ± 8	2×3	1.0	1.5	3×3	0.3	—	—
8	10–11 Jan. 1966	2.5	2.9 ± 0.5	10% μ^- < 1% π^-	90 ± 4	2×6	1.0	1.5	3×3	0.13	6.1 ± 0.6	40

* Ratio of ^{11}C activity in plastic target to the ^{11}C activity in the surrounding "dummy" target. The "dummy" target is a plastic scintillator, surrounding 2 cm wide the entire target.
** The high pion contamination was due to the instalment of a "radio-frequency separator" into the beam.

Table 1. Some technical details of the irradiations.

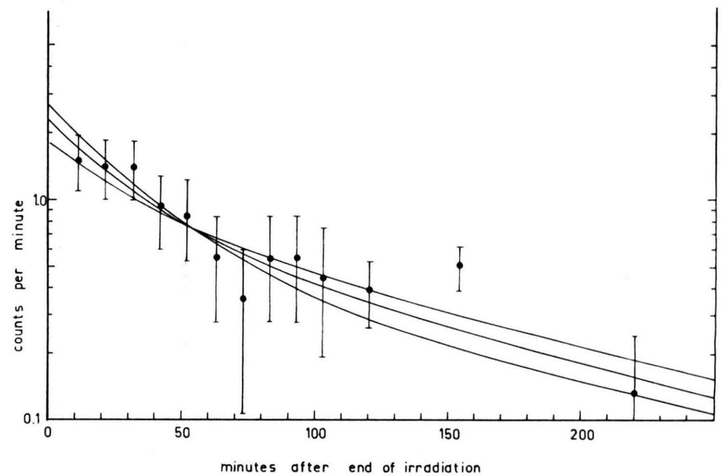

Fig. 2. Resolution of decay curve of ^{11}C and ^{18}F in aluminium targets bombarded with antiprotons as observed in the γ-γ annihilation coincidence counter. A background of 0.13 cpm has already been subtracted. The central curve shows the best fit to the data, and the two others correspond to one standard deviation on either side of the best value for the computed activity ratio.

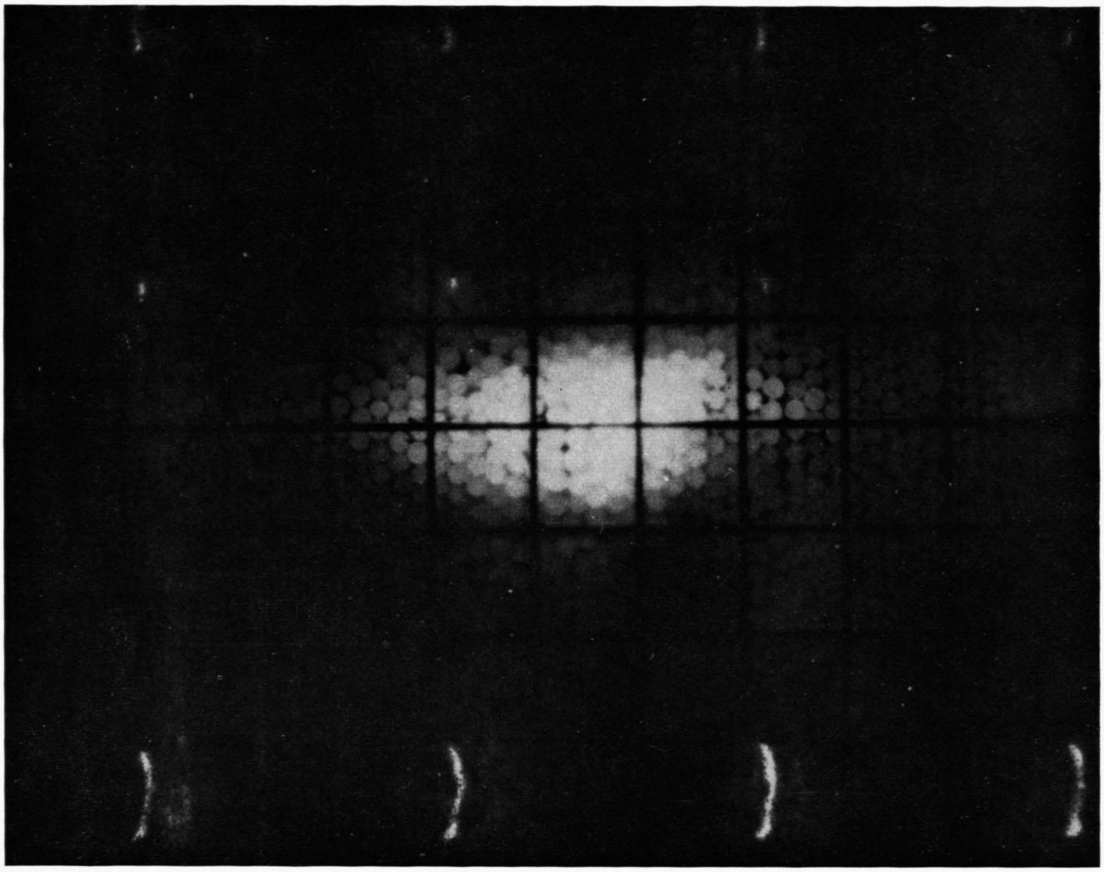

Fig. 1. Picture made with a beam-image intensifying camera. Approximately 3×10^6 $\bar{p}$ traversed the camera. One black square is 1 cm × 1 cm. The target was placed at the centre and had a dimension of 2 cm × 3 cm.

Run	Particle	Momentum (GeV/c)	Length of irradiation (min)	Observed decay rates at end-of-bombardment (cpm)		
				^{11}C in ^{12}C	^{11}C in Al	^{18}F in Al
5−2	$\bar{p}$	3.0	113	127 ± 4	1.91 ± 0.55	0.78 ± 0.14
5−1	π^-	3.0	5.13	1306 ± 15	17.4 ± 1.3	3.40 ± 0.27
6−1	$\bar{p}$	3.0	84	—	1.67 ± 0.33	0.34 ± 0.09
6−1	π^-	3.0	13.5	—	24.1 ± 1.6	4.58 ± 0.31
8−3	$\bar{p}$	2.5	105	42.8 ± 3.1	1.58 ± 0.54	0.73 ± 0.15
8−2	π^-	2.5	20	1184 ± 38	31.1 ± 2.4	8.22 ± 0.70

Table 2. Observed decay rates and irradiation lengths.

agreement with more accurate values obtained elsewhere. In this last experiment the flux was also estimated using a nuclear emulsion. It gives about 30% more flux than the counters. The figures quoted in Table 3 are derived entirely from the scintillation flux counters.

	This work (run 8−2 and 8−3)		Ref. 7	
Bombarding particle	π^-	$\bar{p}$	π^-	$\bar{p}$
Momentum (GeV/c)	2.5	2.5	2.2	3.8
σ(mb)	33 ± 7	40 ± 10	21.7 ± 1.7	30 ± 9

Table 3. Absolute cross-sections for $^{12}C \rightarrow {}^{11}C$ reactions.

Irradiations with π^- instead of $\bar{p}$ were carried out in the same target location. All that was necessary to change from one particle to the other was an adjustment in the current in one of the analyser magnets upstream from the target. The π^- flux was about 100 times bigger than the $\bar{p}$ flux. Therefore irradiation times with π^- were made considerably shorter. Apart from this difference in irradiation time, the experimental parameters were thus strictly comparable in the two exposures in any one running period. The experiments have been scattered over a period of some two years, during which time there have been changes in the exact dimensions of targets and in the detection efficiencies of the counting systems, but such changes do not influence the results of any one run wherein at least one π^- and one $\bar{p}$ irradiation were made under identical conditions.

In all experiments a composite target of aluminium and plastic scintillator was used. The central part was a sandwich of a block of aluminium either 1 cm thick or 1.5 cm with a plastic scintillator 1 cm thick on one side. This assembly was positioned inside an outer frame of plastic scintillator which was used to indicate the fraction of beam not properly focused on the central part.

Activities were measured in the plastic scintillators by coupling them directly to photomultipliers in a standard way, and in the aluminium by $\gamma-\gamma$ annihilation coincidence counting. These methods closely follow those of Poskanzer and Remsberg [7].

Decay curves were analysed manually [12] and by using the CERN IBM 7090 Computer [13] the methods give good agreement. The half-lives assumed were 20.5 min for ^{11}C and 111 min for ^{18}F. The presence of ^{13}N in the irradiated aluminium was systematically ignored. There is therefore a small systematic error in all the values for ^{11}C formed in Al, but this is of no significance in considering the trends of the results as calculated. Relative cross-sections were calculated in the conventional way making corrections where necessary for non-uniformity in particle flux.

2. Technical Details

a) Bombardments

In each run an exposure to π^- was always carried out first. The beam was located using the image intensifying camera and the target put in position to intercept the highest possible flux on the central plastic-aluminium sandwich. Bombardment times were between 5 and 20 minutes. The antiproton exposure was carried out in the same way with exposures up to 100 min using a second identical target. Confirmation that the placing of the target in the antiproton beam was satisfactory was given by comparing the ^{11}C activities in the central and peripheral scintillators. The fraction of beam intercepted by the central target varied between (44 ± 8)% and (90 ± 4)%. (Further details are given in Table 1.)

b) Counting

The plastic scintillator blocks were placed on photomultipliers and covered with aluminium reflectors. Backgrounds were reduced by using 5 cm lead shield-

[12] K. F. Chackett, Nucl. Instr. and Methods (in press).

[13] The authors are grateful to Ch. Gfeller for permission to use his programme.

ing. In the best experiment a bias level was set by using the 59 keV γ rays from ^{241}Am which provided an arbitrary lower limit to the observed β^+ spectrum. We can then, following POSKANZER and REMSBERG [7], take a $95 \pm 2\%$ counting efficiency for the ^{11}C positrons.

For the annihilation coincidence counting we used two 2″ × 2″ sodium iodide crystals or, in the last two experiments, two 3″ × 3″ crystals, placed as close together as possible. With rather narrowly-set discriminator levels on the annihilation photopeaks the 3″ crystals gave a 6% detection efficiency and a background of 0.13 – 0.30 c.p.m. This figure for the efficiency was determined by counting the ^{11}C induced in a block of plastic scintillator both by internal scintillations and in the annihilation-coincidence system. This method is not quite reliable because we could not be sure that the ^{11}C activity was distributed in the same way in the scintillator block as the ^{11}C and ^{18}F would be in the aluminium, but the error must have been small compared to some others inherent in the experiment. In all cases counting was carried out over at least one, and nearly always two, half-periods of the ^{18}F decay, after which statistical errors became unmanageable.

Details of the bombardment conditions and counting rates obtained are shown in Table 2, and Fig. 2 is a typical decay curve of the ^{11}C and ^{18}F in Al.

3. Results and Discussion

In Table 3 are collected our results for the absolute formation cross-section of ^{11}C from ^{12}C [14]. As can be seen, there is no evidence for the reaction cross-section for antiproton activation being significantly different from that for π^- activation from our own experiment. There is probably a systematic error accounting for the difference between our figure for π^- and that given by POSKANZER and REMSBERG [7] for π^-. We can safely conclude that we find no significant difference in the $^{12}C \rightarrow {}^{11}C$ cross-section as between pions and antiprotons as bombarding particles. (It is true that POSKANZER and REMSBERG used a slightly lower π^- momentum than in our work but the difference is insignificant.)

We do not think that any true difference in the cross-sections has been vitiated by the effects of secondary particles produced in the target or camera. Thus REEDER [15] found only a 7% secondary particle contribution to the reaction $^{12}C(\pi^-, \pi^- n)^{11}C$ in a 2.5 inch thick plastic scintillator. Also the threshold for secondary particles for initiating reactions giving ^{11}C and ^{18}F in aluminium will be higher, so that secondary effects should be smaller on this account in our experiment with the aluminium target. However the main emphasis of our work is on the direct comparison of π^- and $\bar{p}$ induced reactions in Al, as explained earlier. We have calculated the three cross-section ratios

$$A = \frac{\sigma_{^{27}Al}(^{11}C)}{\sigma_{^{12}C}(^{11}C)}, \quad (1)$$

$$B = \frac{\sigma_{^{27}Al}(^{18}F)}{\sigma_{^{12}C}(^{11}C)}, \quad (2)$$

$$C = \frac{\sigma_{^{27}Al}(^{11}C)}{\sigma_{^{27}Al}(^{18}F)} \quad (3)$$

whose values appear in Table 4.

Run	Particle	$A = \frac{\sigma_{27Al}(^{11}C)}{\sigma_{12C}(^{11}C)}$	$B = \frac{\sigma_{27Al}(^{18}F)}{\sigma_{12C}(^{11}C)}$	$C = \frac{\sigma_{27Al}(^{11}C)}{\sigma_{27Al}(^{18}F)}$	Ratios for each run		
					$\frac{A_{\bar{p}}}{A_{\pi^-}}$	$\frac{B_{\bar{p}}}{B_{\pi^-}}$	$\frac{C_{\bar{p}}}{C_{\pi^-}}$
5—2 5—1	$\bar{p}$ π^-	$C_1 . (1.51 \pm 0.43)$ * $C_1 . (1.32 \pm 0.10)$ *	$C_2 . (1.18 \pm 0.22)$ * $C_2 . (1.32 \pm 0.13)$ *	1.32 ± 0.46 1.03 ± 0.11	1.14 ± 0.34	0.89 ± 0.18	1.28 ± 0.47
6—1 6—1	$\bar{p}$ π^-	— —	— —	2.30 ± 0.76 1.18 ± 0.10			1.94 ± 0.68
8—3 8—2	$\bar{p}$ π^-	0.28 ± 0.11 0.20 ± 0.03	0.26 ± 0.07 0.23 ± 0.03	1.11 ± 0.42 0.92 ± 0.11	1.41 ± 0.49	1.15 ± 0.26	1.21 ± 0.50
				Weighted man values	1.24 ± 0.28	0.97 ± 0.15	1.38 ± 0.31

* C_1 and C_2 are undetermined constants for the ratio of counting efficiencies.

Table 4. Cross-section ratios.

[14] This idea of studying the same nuclear reaction with various incident particles could be pursued even further. A preliminary measurement of the $^{12}C(K^-, K^-n)^{11}C$ cross-section for 800 MeV/c negative kaon gave a result of (56 ± 18) mb.

[15] P. L. REEDER, University of California Report, UCRL-10031 [1962], (unpublished).

It is evident that the weighted mean values as given in Table 4 *do not differ significantly from unity,* since those values are the ratio of $\bar{p}$ and π^- reaction cross-section ratios and they give directly the effect of $\bar{p}$ in comparison to π^-. (Here the uncertainties in the flux determination and counting efficiencies have cancelled.) *This implies that no difference in the behaviour of $\bar{p}$ and π^- induced reactions could be observed.*

The precision of the experiment is of course not high, and since this is almost entirely caused by the low intensity of the $\bar{p}$ beam it appears that an experiment of better significance will have to await a considerable increase in the available number of antiprotons. However, we hope to extend measurements to heavier target nuclei in which effects might be more easily found.

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