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ANTIPROTON ABSORPTION CROSS-SECTION

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Parametrization of nuclear absorption cross-section of antiprotons is discussed. A simple procedure of performing the parametrization is presented and used to predict the values of the absorption cross-section.

1. INTRODUCTION

During the last fifteen years or so several experiments have reported measurements of the absorption cross-section of $\bar{p}$ on many complex nuclei. Such measurements have been made at different values of the $\bar{p}$ laboratory momentum. The relevant information is given in Table 1.

As seen from Table 1, the absorption cross-section has been measured over a wide range (from 368 MeV/c to 280 GeV/c) of the incident momentum of the $\bar{p}$, and on a large number of nuclei from He to U. Of course, gaps in the incident momentum range exist, and there are many nuclei on which measurements have not yet been made. It must also be pointed out that the information on low energy antiproton-nucleus ($\bar{p}$-A) interactions is meagre, though a great deal of interest in such interactions has been aroused on account of the CERN facility Low Energy Antiproton Ring (LEAR). However, sufficient data are now available on the basis of which the dependence of the $\bar{p}$ absorption cross-section on complex nuclei can be more systematically studied, and its dependence on the $\bar{p}$ incident momentum and the mass of the complex nucleus can be examined.

Analysis of the data should provide insight not only into the nature of the $\bar{p}$ interaction with nuclear matter but also information useful in the determination of parameters of the $\bar{p}$ — nucleus potential. It is for these reasons that an analysis of the entire published data (as available to us) is being attempted in this work. We believe this is the first work of this kind. In this work, only the relevant part of the published data is given. The rest of the data may be found elsewhere [1—8].

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Table 1

Experimental measurements

S. No.	$\bar{p}$ lab-momentum	Complex Nuclei	Reference
1.	(368 ± 43) MeV/c	C, Pb	[7] Cohn et al. (1984)
2.	(485, 597) MeV/c	C, Al, Cu	[3] Aihara et al. (1981)
3.	(513, 633) MeV/c	Al, Cu, Pb	[2] Ashford et al. (1985)
4.	Six values between (470 and 880) MeV/c	C, Al, Cu	[8] Nakamura et al. (1984)
5.	In the region (1.0 to 3.3) GeV/c in 0.05 GeV/c steps	C, Cu	[6] Abrams et al. (1971)
6.	(6.65, 13.3 and 25) GeV/c	Li, Be, C, Al Cu, Sn, and Pb	[1] Denisov et al. (1973)
7.	(20, 30 and 40) GeV/c	He, Li, Be, C, Al Cu, Sn, Pb and U	[4] Allaby et al. (1971)
8.	(60, 200 and 280) GeV/c	Li, C, Al, Cu, Sn and Pb	[5] Carroll et al. (1979)

2. SUMMARY OF THE EARLIER ANALYSIS

(a) Parametrization

In earlier works [1—6] the ($\bar{p}$-A) absorption cross-section (σ_a) has been parametrized according to the expression

$$\sigma_a = \sigma_0 A^{\alpha}, \qquad (1)$$

where σ_0 and α are adjustable parameters and A is the mass number of the nucleus with which $\bar{p}$ interacts. For obtaining a better fit of the experimental data, the values of the two parameters, σ_0 and α, are adjusted by the method of least squares. It is observed that the value of the parameter α remains almost constant for all nuclei at one value of the $\bar{p}$ incident momentum. The values of this parameter chosen previously are in the range of 0.61 to 0.713 for the $\bar{p}$ momentum varying up to 280 GeV/c.

(i) Ambiguity

The fact that the parametrization involves two adjustable parameters leaves room for ambiguity and makes the task laborious and time-consuming. For example, the values of σ_0 and α obtained [1] from the least-squares fitting for the nuclei Li, Be, C, Al, Cu, Sn and Pb at a $\bar{p}$ — momentum of 6.65 GeV/c are 72.6 ± 1.7 and 0.624 ± 0.006, respectively. However, these are average values found for the above-mentioned seven nuclei. To reproduce the experimental data (i.e., the ($\bar{p}$-A) absorption cross-section) for any of the seven nuclei, the average values of σ_0 and α have to be varies. This can be done by keeping fixed the value of either of the two parameters and varying the value of the other parameter, or by varying the values of both the parameters. Thus, there may be three sets of values of σ_0 and α for reproducing the experimental resuts for one nucleus and for one value of the $\bar{p}$ momentum. This introduces ambiquity. There is no scope for getting unambiquous results.

(ii) Limited Applicability

The average values of σ_0 and α obtained for a particular set of nuclei (e.g., the set of seven nuclei mentioned above) are applicable only to this set of nuclei (i.e., only to those nuclei which are included in the X^2-fitting) for one value of the $\bar{p}$ momentum. In other words, the values of σ_0 and α are specific to a particular set of nuclei for which experimental values of absorption cross-sections are available for a given value of the $\bar{p}$ momentum.

These values, therefore, cannot be used to discern any systematic, regular behaviour of the $\bar{p}$-nucleus absorption cross-section. Nor can these values be used to predict the values of a $\bar{p}$-nucleus absorption cross-section in other nuclei if these have been deduced for a group of nuclei at some particular value of the $\bar{p}$-momentum. Not only this, the absorption cross-section of $\bar{p}$ in the same group of nuclei cannot be estimated at another value of the $\bar{p}$-momentum if it is known at one value of the $\bar{p}$-momentum.

iii) Reduced Utility

Thus, the procedure of parametrization outlined above (and, adopted hitherto) has only one merit. The merit is that the experimental data can be reproduced for a given set of nuclei for one value of the $\bar{p}$-momentum. However, the ambiguity and limited applicability, as discussed herein, reduce its utility. The procedure fails to provide any guidance as regards the behaviour of different nuclei at different values of the $\bar{p}$-momentum.

(b) Other techniques

Attempts have been made to reproduce the experimental results of the ($\bar{p}$-A) absorption cross-section by making use of the optical model and Glauber's multiple scattering approaches [9]. However, ambiguity and lengthiness of the procedure involving several parameters do not permit satisfactory reproduction of the data.

3. PRESENT ANALYSIS

An analysis of the entire published data (available to us) on the ($\bar{p}$-A)

absorption cross-section [1—8] is made in the present work with a view to finding whether

(i) the procedure of fitting the data can be simplified
(ii) the number of parameters can be reduced
(iii) the ambiguity can be eliminated; and
(iv) any regular features of the cross-section as a function of nuclear mass, and the momentum of the $\bar{p}$ can be inferred.

4. PROCEDURE OF THE ANALYSIS

The fitting of the ($\bar{p}$-A) absorption cross-section (σ_a) starts, in this work also, with the expression (1) given in sec. 2(a), viz,

$$\sigma_a = \sigma_0 A^{\alpha}.$$

The results of this work indicate that the fitting reproduces experimental data to a fair extent if the parameter α is assigned a fixed value, namely, if $\alpha = 0.68$. Thus, only one parameter σ_0 is involved in the fitting procedure while the fitting done earlier [1—6] by other workers used two adjustable parameters as mentioned in section 2(a).

Although expression (1) yielded satisfactory results, two questions remained to be answered.

1. Is expression (1) applicable to σ_a for all nuclei and at all values of the $\bar{p}$-momentum and,
2. Is the numerical value (0.68) of the index α valid for every nucleus and for each $\bar{p}$-momentum?

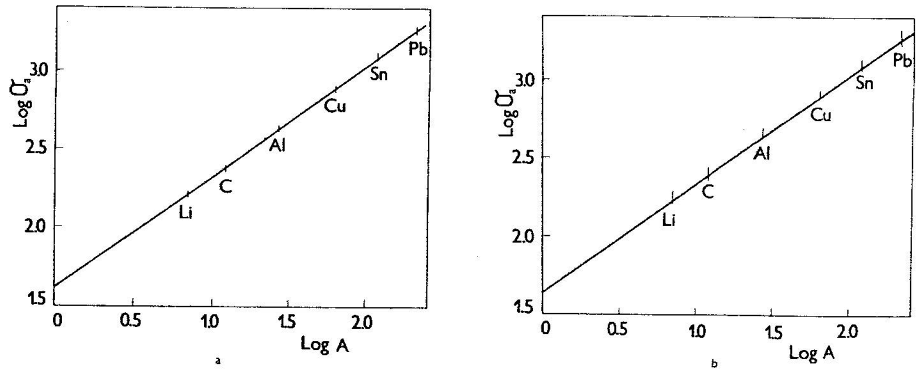
It may be mentioned that expression (1) had been applied only to a limited set of data [1, 3]. Consequently, answers to questions raised above were urgently needed.

5. VARIATION OF THE PROCEDURE

Now that a lot more data have become available, the procedure of analysis has been varied even though the starting step is still expression (1). However, now the value of the index α is not taken fixed (i.e., $\alpha \neq 0.68$). To estimate the values of the parameters σ_0 and α the logarithm of both sides expression (1) is taken. Thus,

$$\log \sigma_a = \alpha \log A + \log \sigma_0 \quad (2)$$

This is the equation of a straight line. Therefore, a graph between the two known variables, $\log \sigma_a$ and $\log A$, for any value of the $\bar{p}$-momentum, should provide values of the two parameters; the slope of the line gives the value of the parameter α while the intercept of the line gives that of the parameter σ_0.



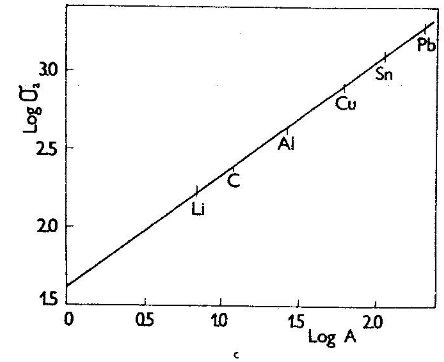
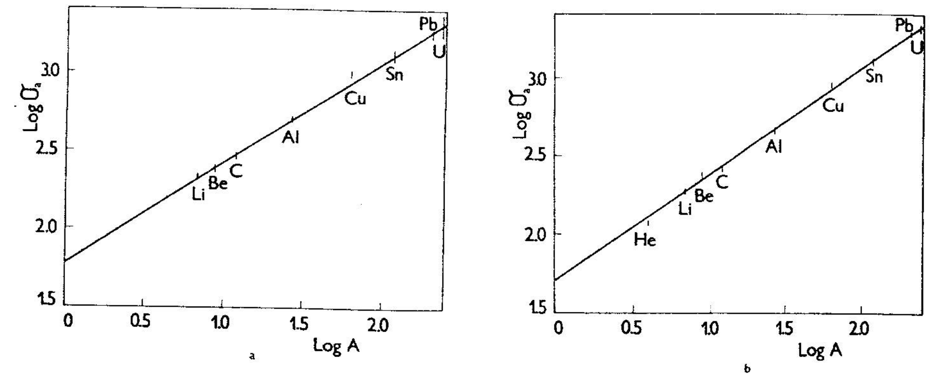


Fig. 1 (a) — Log σ_a versus log A, $\bar{p}$ momentum = 280 GeV/c; (b) — $\bar{p}$ momentum = 200 GeV/c; (c) $\bar{p}$ momentum = 60 GeV/c

6. RESULTS AND DISCUSSION

$\log \sigma_a$ versus $\log A$ for various values of the $\bar{p}$ momentum are shown in Figs. 1 to 5. The slope (tan Θ) of the curves and their intercepts on the Y-axis provide values of the parameters α and σ_0. The values of these parameters along with other relevant data are presented in Tables 2 to 6.

It is noteworthy that the entire experimental data, (for $\bar{p}$ momentum from 0.485 GeV/c to 280 GeV/c) follow the pattern suggested by expression (2). A slight, irregular deviation from the general pattern (of the data falling on a straight line) is seen (Figs. 2 and 3) in the case of light nuclei He, Li and Be in the sense that the experimental data for these nuclei do not exactly fall on a straight line. This deviation (at high values of the $\bar{p}$ momentum from 6.65 GeV/c onwards) is probably a consequence of the uncertainties of experimental data. In the absencse of more and systematic deviations it would be hazardous to draw any inferences regarding any possible difference in the response of a



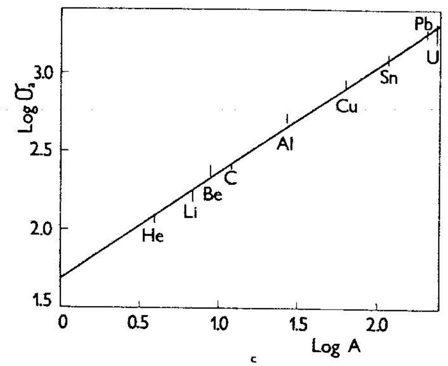


Fig. 2 (a) — Log σ_a versus log A, $\bar{p}$ momentum = 20 GeV/c; (b) — $\bar{p}$ momentum = 30 GeV/c; (c) — $\bar{p}$ momentum = 40 GeV/c

new-nucleon system and that of a many-nucleon system to the $\bar{p}$ having the same (high) linear momentum.

Figs. 1, 2, and 3 show the behaviour of the absorption cross-section of $\bar{p}$ having the momentum from 6.65 GeV/c to 280 GeV/c in agreement with expression (2). However, Fig. 4 tells a different tale. The experimental data of Ashford et al. [2], used in Fig. 4, do not fall on a straight line. At the same time, the calculated values of σ_a (obtained from an optical model fit) of these authors do fall on a straight line. Naturally, for purposes of this work, so far as drawing general inferences is concerned, the calculated values of Ashford et al. [2] are taken into consideration. It is worth mentioning that the calculated value of σ_a of Ashford et al. [2] for the $\bar{p}$ absorption in Pb is in agreement with the corresponding value estimated in the present work. The $\bar{p}$ momentum varies from 0.514 GeV/c to 0.633 GeV/c at which Ashford et al. have reported their results.

Fig. 5 shows that σ_a for the $\bar{p}$ momentum from 0.485 GeV/c to 0.597 GeV/c follows the expected behaviour, i.e., the data points fall on a straight line.

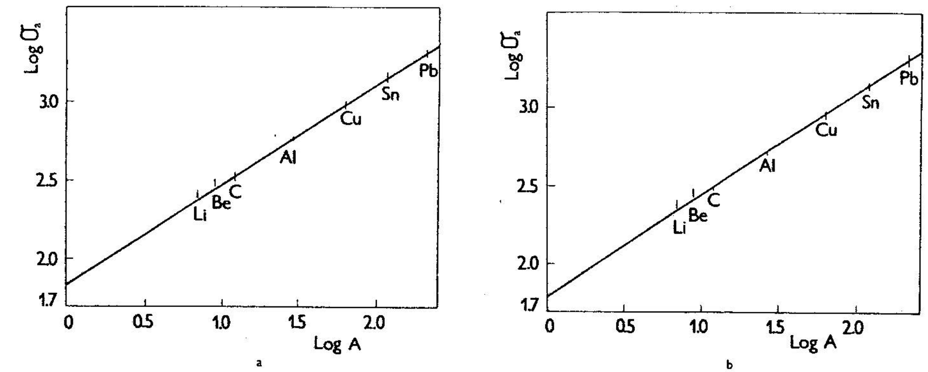
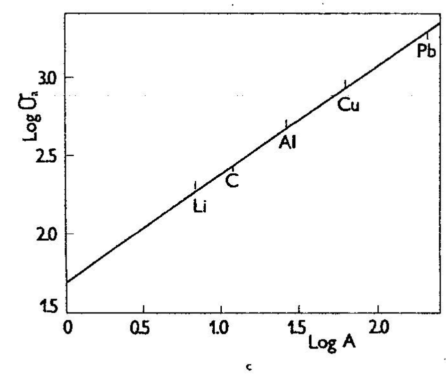


Fig. 3 (a) — Log σ_a versus log A, $\bar{p}$ momentum 6.65 GeV/c; (b) — $\bar{p}$ momentum 13.3 GeV/c; (c) — $\bar{p}$ momentum 25.0 GeV/c



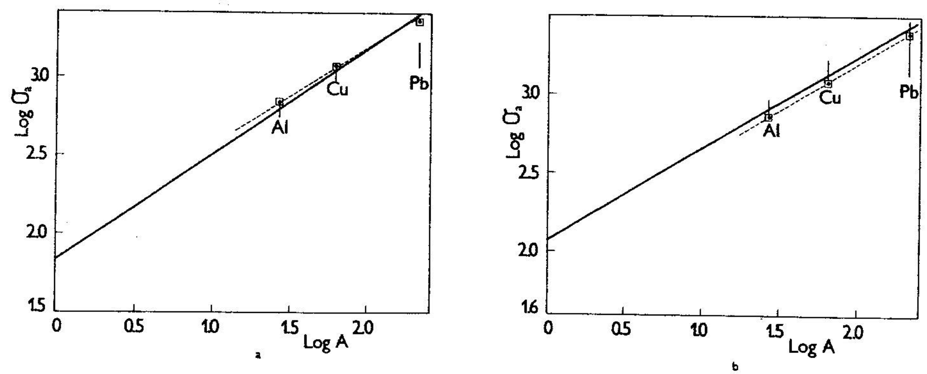


Fig. 4 (a) — Log σ_a versus log A, $\bar{p}$ momentum 0.633 GeV/c; –□–– — OM Fit [2]; (b) — $\bar{p}$ momentum 0.514 GeV/c, –□–– — OM Fig [2]

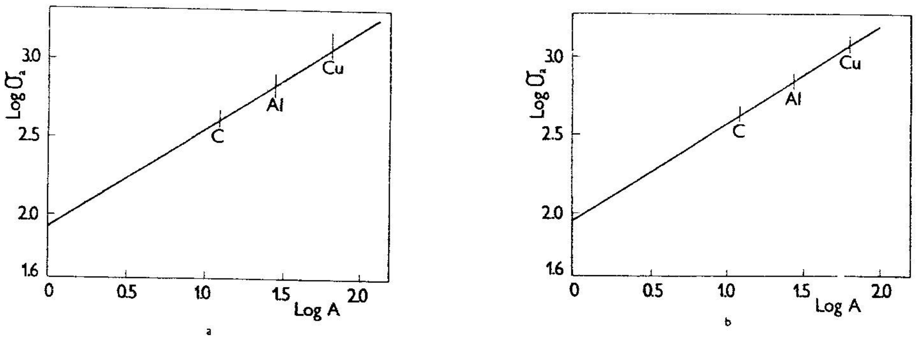


Fig. 5 (a) — Log σ_a versus log A, $\bar{p}$ momentum 0.485 GeV/c; (b) — $\bar{p}$ momentum 0.597 GeV/c

In can, thus, be inferred that the entire available experimental data, for all values of the $\bar{p}$ momentum and for all nuclei (for which experiments have been made and whose results have been reported) follow the pattern suggested by expression (2). In the light of this inference it is tempting to generalize and say that expression (2) is or should be valid for all $\bar{p}$ momenta and for all nuclei (i.e., even for those $\bar{p}$ momenta and nuclei for which experimental data are not available) and that the Figs. 1 to 5 could be used for predicting the values of the $\bar{p}$ absorption cross-section, if not for all $\bar{p}$ momenta, at least for all nuclei at a given value of the $\bar{p}$ momentum. However, the temptation should be tempered with caution for several reasons:

(a) The experimental values of σ_a of Ashford et al. [2] for the $\bar{p}$ momenta of 0.514 GeV/c and 0.633 GeV/c do not fall, as already mentioned, on a straight line and obviously do not obey expression (2). What does this disagreement mean?

(b) The experimental values of σ_a for low values of the $\bar{p}$ momenta are not numerous to permit generalization. It is also worth mentioning that, as seen from Table 8, the value of σ_a at the $\bar{p}$ momentum of 0.368 GeV/c (the lowest value at which experimental data are available), is (730 ± 180) mb for C and (5300 ± 1700) mb for Pb while (as seen from Tables 2 to 6) the values of σ_a for C and Pb go on decreasing, becoming (239 ± 8) mb and (1856 ± 77) mb at the $\bar{p}$ momentum of 280 GeV/c, respectively. Even at the $\bar{p}$ momentum of the low value of (0.485 + 0.036) GeV/c, σ_a is (410 ± 35) mb for C (Table 6) while at the $\bar{p}$ momentum of 0.514 GeV/c, σ_a for Pb is (2100 ± 700) mb (Table 5). These values show that as the $\bar{p}$ momentum decreases from 0.485 GeV/c to 0.368 GeV/c (i.e., by 0.117 GeV/c) the cross-section σ_a increases from (410 ± 35) mb to (730 ± 180) mb in the case of C. Similarly, a decrease from 0.514 GeV/c to 0.368 GeV/c (i.e., by 0.146 GeV/c) in the $\bar{p}$ momentum results in an increase in the value of σ_a from (2100 ± 700) mb to (5300 ± 1700) mb in the case of Pb. It

Table 2

$\bar{p}$ absorption cross-section and values of parameters σ_0 and α
$\bar{p}$ momentum 60 GeV/c, 200 GeV/c and 280 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)						Results of Carroll et al [5]		Results of this work	
	Li	C	Al	Cu	Sn	Pb	σ_0	α	σ_0	α
60	170 ± 5	242 ± 7	439 ± 14	794 ± 24	1218 ± 38	1805 ± 56	43.50 ± 1.73	0.698 ± 0.010	43.65	0.696
200	163 ± 5	236 ± 7	435 ± 14	772 ± 24	1239 ± 40	1793 ± 58	41.08 ± 1.67	0.710 ± 0.011	41.69	0.704
280	166 ± 6	239 ± 8	422 ± 15	782 ± 29	1236 ± 51	1856 ± 77	41.05 ± 1.91	0.713 ± 0.013	40.74	0.713

Table 3

$\bar{p}$ absorption cross-section and values of parameters σ_0 and α
$\bar{p}$ momentum 20 GeV/c, 30 GeV/c, and 40 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)									Results of Allaby et al. [4]		Results of this work	
	He	Li	Be	C	Al	Cu	Sn	Pb	U	σ_0 (mb)	α	σ_0 (mb)	α
20		215 ± 7	240 ± 10	290 ± 15	500 ± 20	965 ± 66	1300 ± 120	1810 ± 150	2030 ± 320	59.1 ± 2.6	0.648 ± 0.010	60.26	0.639
30	117 ± 5	188 ± 4	235 ± 6	258 ± 6	457 ± 11	890 ± 30	1210 ± 45	1880 ± 65	2020 ± 125	50.9 ± 2.4	0.674 ± 0.009	50.12	0.675
40	119 ± 5	168 ± 8	226 ± 7	257 ± 5	490 ± 15	820 ± 30	1240 ± 70	1790 ± 80	1820 ± 200	49.9 ± 2.4	0.674 ± 0.010	48.42	0.676

Table 4

$\bar{p}$ absorption cross-section and values of parameters σ_0 and α
$\bar{p}$ momentum 6.65 GeV/c, 13.3 GeV/c and 25.0 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)							Results of Denisov et al. [1]		Results of this work	
	Li	Be	C	Al	Cu	Sn	Pb	σ_0 (mb)	α	σ_0 (mb)	α
6.65	252 ± 6	296 ± 6	330 ± 7	558 ± 10	952 ± 20	1421 ± 53	2056 ± 42	72.6 ± 1.7	0.624 ± 0.006	69.18	0.634
13.3	233 ± 3	275 ± 4	313 ± 6	526 ± 14	921 ± 20	1377 ± 40	2026 ± 44	67.0 ± 1.2	0.636 ± 0.005	63.10	0.648
25.0	200 ± 5	—	265 ± 6	480 ± 9	862 ± 20	—	1849 ± 45	58.7 ± 1.4	0.629 ± 0.007	48.98	0.683

Table 5

$\bar{p}$ absorption cross-section and values of parameters σ_0 and α
$\bar{p}$ momentum 0.514 GeV/c and 0.633 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)			Results of Ashford et al. [2]		Results of this work	
	Al	Cu	Pb	σ_0 (mb)	α	σ_0 (mb)	α
0.514	770 ± 60	1420 ± 100	2100 ± 700	67.9		117.5	0.588
0.633	620 ± 500	1100 ± 100	1400 ± 250	91.2	0.61	67.61	0.669

Table 6

$\bar{p}$ absorption cross-section and values of parameters σ_0 and α
$\bar{p}$ momentum 0.485 ± 0.036 GeV/c and 0.597 ± 0.024 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)			Results of Aihara et al. [3]		Results of this work	
	C	Al	Cu	σ_0 (mb)	α	σ_0 (mb)	α
0.485 ± 0.036	410 ± 35	663 ± 86	1186 ± 154	87.9 ± 16.3	0.62 ± 0.06	83.18	0.634
0.597 ± 0.024	422 ± 25	679 ± 66	1188 ± 106			89.13	0.620

Table 7

$\bar{p}$ absorption cross-section and values of parameters σ_0 and α
$\bar{p}$ momentum 0.628 GeV/c, 0.782 GeV/c and 0.881 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)		Results of Nakamura et al. [8]		Results of this work	
	Al	Cu	σ_0 (mb)	α	σ_0 (mb)	α
0.626	727 ± 30	1197 ± 40			104.7	0.588
0.782	720 ± 30	1198 ± 40			104.7	0.586
0.881	661 ± 30	1118 ± 40	Not estimated		87.0	0.616

Table 8

$\bar{p}$ absorption cross-section and values of parameters σ_0 and α
$\bar{p}$ momentum 0.368 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)		Results of Cohn et al. [7]		Results of this work	
	C	Pb	σ_0 (mb)	α	σ_0 (mb)	α
0.368	730 ± 180	5300 ± 1700	Not estimated		130.3	0.695

Table 9

$\bar{p}$ absorption cross-section and the values of parameters σ_0 and α
$\bar{p}$ momentum 1.6 GeV/c to 3.2 GeV/c in steps of 0.2 GeV/c

$\bar{p}$ momentum (GeV/c)	Nuclear absorption cross-section, σ_a (mb)		* Results of Abrams et al. [8]		Results of this work	
	C	Cu	σ_0 (mb)	α	σ_0 (mb)	α
1.6	396.33 ± 1.20	1131.01 ± 6.35			85.11	0.621
1.8	391.53 ± 1.20	1099.24 ± 6.35			83.18	0.623
2.0	385.52 ± 1.20	1080.18 ± 6.35			86.10	0.608
2.2	379.52 ± 1.20	1080.18 ± 6.35			79.43	0.628
2.4	373.51 ± 1.20	1067.47 ± 6.35			74.13	0.642
2.6	366.31 ± 1.20	1048.41 ± 6.35			72.44	0.644
2.8	360.30 ± 1.20	1042.06 ± 6.35			72.44	0.644
3.0	349.49 ± 1.20	1029.35 ± 6.35			68.39	0.653
3.2	341.08 ± 1.20	1010.29 ± 6.35	68 ± 7	0.65 ± 0.01	66.07	0.656

* Abrams et al obtained the average values of σ_0 and α at 3.2 GeV/c

is obvious, therefore, that more experimental values of σ_a at lower values of the $\bar{p}$ momentum would be needed to draw any meaningful inferences. It is also noteworthy that at a low $\bar{p}$ momentum (0.368 GeV/c) the error in the value of σ_a is about 25% for the C nucleus and about 32% for the Pb nucleus. Thus, it cannot be said without any measure of certainty that expression (2) is, or would be, equally valid at lower values of the $\bar{p}$ momenta.

(C) The third cause for caution lies in the likely response of very light nuclei like He, Li and Be to the $\bar{p}$ momenta of different, particularly lower values. Will the response be the same as that of heavier nuclei?

The only safe statement that can be made is that expression (2) seems to be generally valid over the $\bar{p}$ momentum range from (0.485 ± 0.036) GeV/c to 280 GeV/c, and that over this range the value of σ_a can be predicted, for a given value of the $\bar{p}$ momentum, for complex nuclei for which experimental results are not available. Figs 1 to 5 become, therefore, very important. The value of σ_a for any complex nucleus can be obtained from them.

In certain cases [6—8], experimental values of σ_a for a given $\bar{p}$-momentum are available only for two nuclei as seen from Tables 7 to 9. It is obvious that no curve can be plotted on the basis of two points. However, assuming that the aforementioned inference regarding the validity of expression (2) is correct, we have hazarded a guess about the values of the parameters α and σ_0 which are presented in the last columns of tables 7 to 9.

The values of the parameters α and σ_0 estimated in this work (from Figs. 1, 2, 3 and 5) compare with the values of these parameters as obtained by other workers from a chi-square fit. The two sets of values are given in the last columns of Tables 2, 3, 4 and 6. However, the values obtained from Ashford et al. [2] of these parameters considerably differ from the corresponding values of this work (Table 5). This difference falls in perspective if the fact that experimental datum of these authors does not obey expression (2) is taken into account. If the datum behaves differently, the values of the parameters obtained from the datum are expected to have different values.

The unique set of the values of the parameters α and σ_0 obtained in this work automatically takes care of the ambiguity encountered in other methods of parametrization of the nuclear absorption cross-section of $\bar{p}$. It is no more possible to change the value of one parameter and compensate the change by adjusting the value of the other parameter. Therefore, it seems to us that the parametrization suggested in this work is reliable and can be used not only to reproduce experimental data but also to predict the value of σ_a even in those nuclei in which the $\bar{p}$ absorption has not been studied so far.

7. CONCLUSIONS

(i) A simple method of parametrization of σ_a which yields unambiguous results is possible.

(ii) The value of σ_a for nuclei in which the $\bar{p}$ absorption has not been experimentally studied can be predicted for a given value of the $\bar{p}$ momentum.

(iii) The validity of the analysis of this work in the case of light nuclei as well as, and more particularly, for low values of the $\bar{p}$ momentum (say below 450 MeV/c) can be tested only when more relevant experimental data become available.

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ДИФФЕРЕНЦИАЛЬНОЕ СЕЧЕНИЕ АНТИПРОТОННОГО ПОГЛОЩЕНИЯ

Обсуждается параметризация дифференциального сечения ядерного поглощения антипротонов. Описана простая процедура проведения параметризации, которая использована для предсказания значений дифференциаяльного сечения подлощения.