# Nuclear Radii from Antiproton Measurements

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THE antiproton observations which have a bearing on the subject of this conference, are the cross-section measurements. To date the experimental material is scarce and not very precise, nevertheless it has shown interesting peculiarities.

Reviewing the experimental facts, we have measurements of annihilation, reaction, and total cross sections at energies ranging from 190 to 700 Mev. The existing measurements are summarized in Table I.[1–5] For a clear understanding of the meaning of the cross sections, I briefly review the experiments by which they are obtained.

The annihilation cross sections $\sigma_a$ are obtained with apparatus of the type shown in Fig. 1. A certified antiproton enters the box $C^*$ and, if it undergoes annihilation in it, the emerging pions give Čerenkov light which is seen by a bank of 9 photomultipliers. If the antiproton emerges without suffering annihilation and escapes within the cones of 14.6° or 21.5° semiaperture, it is considered as noninteracting. Thus an antiproton undergoing diffraction scattering is counted as *not* interacting. The data from the literature[3,5] (columns 4 and 5 of Table I) give the annihilation and reaction cross sections obtained in this way. The other columns refer to good geometry experiments[2] in which diffraction scattering contributes to the total cross section. We should then have $\sigma_{\text{total}}-\sigma_{\text{reaction}}=\sigma_{\text{diffraction}}$. There is a difficulty in the case of hydrogen where the difference between $\sigma_{\text{total}}$ and $\sigma_{\text{reaction}}$ is practically zero, leaving no room for a commensurate $\sigma_{\text{diffraction}}$. This difficulty cannot at present be resolved. New experiments are necessary.

In addition to these experiments there are several meters of antiproton tracks in photographic emulsions, in which approximately 150 collisions occur.[6,7] This gives a mean free path of 17.7±1.6 cm. This number can be put in a slightly different form: giving to every nucleus in the emulsion a total cross section $r(\bar{p})A^{\frac{1}{3}}$, the value found for $r(\bar{p})$ is $1.72\times10^{-13}$ cm. The energy of the antiprotons in the emulsion goes from 250 Mev at the entrance to a minimum of 10 Mev, below which the antiproton is not distinguishable from an antiproton at rest. With the present data it is futile to try to subdivide the energy intervals in which the collisions occur, because the statistics are too poor. The data show a slight increase of cross section on decreasing velocity, but no quantitative conclusions can be drawn.

The photographic method also allows one to measure small angle scattering, with an interesting result explained later.

Charge exchange scattering has also been observed, and very crude measurements of the cross section[4] are shown in Table I.

In view of the interest that it would have, an attempt has been made to obtain the $\bar{p}n$ cross section by using a $D-H$ difference method. The results are imprecise because the difference method is experimentally difficult and in addition the Glauber correction,[8] which should take into account the shielding of one nucleon from the other in the deuteron, is very large and uncertain. Our present best estimates of the reaction and annihilation cross sections at 450 Mev are

$$\sigma_r=113 \text{ mb}$$
$$\sigma_a= 74 \text{ mb}$$

with an error of about 15 mb from the measurement and an unknown error from the estimation of the Glauber correction. Dr. Glauber has expressed the opinion that

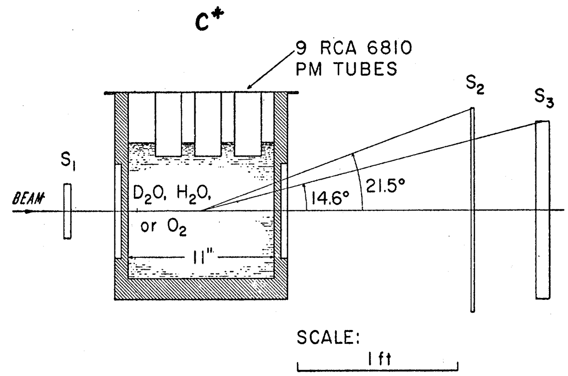


FIG. 1. A typical apparatus for measuring antiproton collision cross sections. The antiproton is certified by scintillator $S_1$, the box $C^*$ contains the absorber, and the photomultiplier tubes recognize annihilation; scintillators $S_2$ and $S_3$ recognize antiproton which pass through.

[1] Chamberlain, Keller, Segrè, Steiner, Wiegand, and Ypsilantis, Phys. Rev. **102**, 63 (1956).
[2] Cork, Lambertson, Piccioni and Wenzel, Phys. Rev. **107**, 248 (1957).
[3] Chamberlain, Keller, Mermod, Segrè, Steiner, and Ypsilantis, Phys. Rev. **108**, 1553 (1957).
[4] Button, Elioff, Segrè, Steiner, Weingart, Wiegand, and Ypsilantis, Phys. Rev. **108**, 1557 (1957).
[5] Agnew, Chamberlain, Keller, Mermod, Rogers, Steiner, and Wiegand, Phys. Rev. **108**, 1545 (1957).
[6] G. Goldhaber, Padova Conference (1957).
[7] Barkas, Birge, Chupp, Ekspong, Goldhaber, Goldhaber, Heckman, Perkins, Sandweiss, Segrè, Smith, Stork, Rossum, Amaldi, Baroni, Castagnoli, Franzinetti, and Manfredini, Phys. Rev. **105**, 1037 (1957).
[8] R. J. Glauber, Phys. Rev. **100**, 242 (1955).

TABLE I. Summary of antiproton cross sections in mb.

| | $\sigma_t$ | $\sigma_t$ | $\sigma_{\text{reaction}}$ | $\sigma_a$ | $\sigma_{ce}$ | $\sigma_t$ | $\sigma_t$ |
|---|---|---|---|---|---|---|---|
| E Mev | 190 | 300 | 450 | 450 | | 500 | 700 |
| H | 135±16 | 104±14 | 104±8 | 89±7 | 3±1.6 | 97±4 | 94±4 |
| D | | | 174±8 | 135±7 | | | |
| Be | | | 365±60 | 170±60 | | 484±60 | 425±50 |
| C | | 655±130 | | | 4±1.5 | | 657±79 |
| O | | | 590±12 | 453±9 | | | |
| Cu | | | 1260±91 | 1040±61 | | | |
| Ag | | | 1633±188 | 1500±157 | | | |
| Pb | | | 3005±250 | 2010±182 | 3.8±4 | | 2330±85 |

we have probably overcorrected our results and that our number is to be considered as an upper limit.

This in a nutshell is the experimental situation. Passing to the interpretation, we discuss separately the antiproton nucleon case from the antiproton nucleus case.

There are several relations based on conservation of isotopic spin, such as[9–12]

$$(d\sigma/d\omega)_{\text{ex},0} \geqslant (k/4\pi)^2[\sigma^t(\bar{p}n)-\sigma^t(p\bar{p})]$$

for the charge exchange cross section at zero angle, which are valid; however, they do not put severe limitations on the data and are all satisfied by the experiments. We are still far from sufficient accuracy to distinguish between $T=1$ and $T=0$ collisions. Taking the results literally, they indicate that the cross section is the same in the two isotopic spin states.

However, a striking fact that emerges is the large value of the ratio between $p\bar{p}$ and $pp$ total cross sections. This is illustrated in Fig. 2. The ratio reaches the value of 4 at 200 Mev.

Ball and Chew have given a very interesting explanation of this phenomenon.[13] Starting from pion theory they observe that the phase shifts in $pp$ scattering in the 150 Mev region can be accounted for by a model having a hard core whose radius is about $\frac{1}{3}\times 1.4\times 10^{-13}$ cm$=\frac{1}{3}$ pion Compton wavelength and a zone in which the potential is calculable from pion theory. This model is very reasonable, and gives the Gartenhaus potential which has been improved by Signell and Marshak by the addition of spin-orbit coupling. It accounts satisfactorily for the $pp$ scattering experiments up to about 150 Mev and has a reasonable pion theoretic foundation —at least with his extremely lucid explanations Professor Chew has convinced me of it. Now they make some changes in this model which are perfectly reasonable and consistent: they replace the hard core with a black core, the blackness being caused by the annihilation of an antiproton hitting it and they change some signs in the mesonic part of the potential as required by meson theory. These changes of signs are brought about by the fact that the mesonic charge of a nucleon has the opposite sign of that of an antinucleon. At present they consider terms corresponding to the exchange of one or two pions.

They then derive an equivalent potential for arbitrary $J$ and parity and calculate cross sections for $pp$ and $p\bar{p}$ scattering. Unfortunately up to now they have considered only $s$ and $p$ waves, which limits the energy to about 150 Mev. The reason for this is that at higher energies the situation created by the attractive potential plus centrifugal barrier is complicated and details near the boundary become important. The numbers obtainable at 140 Mev are given in Table II. There are no accurate measurements to compare with these calculations; for what they may be worth, 5 elastic $p\bar{p}$ collisions in photographic emulsions[6] give a cross section 75±50 mb, but at least the qualitative features are correct and there is real hope that we have the physically correct explanation.

Passing to complex nuclei, there have been several attempts by Nemirowski,[14] Drell, ourselves, and Glass-

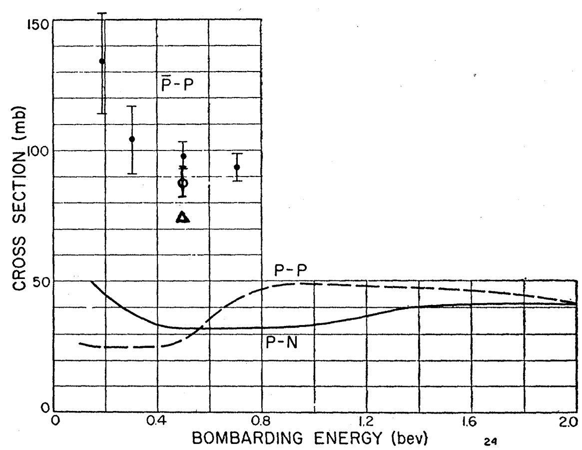


FIG. 2. Comparison of the proton-proton and proton-neutron cross sections with the corresponding cross sections for antiprotons:

● $\sigma_t$ $p$-$\bar{p}$,
○ $\sigma_a$ $p$-$\bar{p}$,
△ $\sigma_a$ $\bar{p}$-$n$.

[9] B. J. Malenka and H. Primakoff, Phys. Rev. **105**, 338 (1957).
[10] D. Amati and B. Vitale, Nuovo cimento 4, 145 (1956).
[11] I. Kobsarev and I. Schmurschkevic, Doklady Akad. Nauk. S.S.S.R. **102**, 929 (1955).
[12] O. Chamberlain, Padova Conference (1957).
[13] J. S. Ball and G. Chew, Phys. Rev. **109**, 1385 (1958).
[14] P. E. Nemirowski, Doklady Akad. Nauk. S.S.S.R. **112**, 411 (1957).

TABLE II. Theoretical cross sections for nucleon-antinucleon interaction[a] (mb).

| $p\bar{p}$ | | $n\bar{p}$ | | $pp$ | $np$ |
|---|---|---|---|---|---|
| 168 (154) | 72 abs. | 148 | 69 | | |
| | 96 sc. | | 79 | 29 | 60 |

[a] See reference 13.

TABLE III. Optical model potentials.

| Projectile | $V$ Mev | $W$ Mev |
|---|---|---|
| Proton | −15 | −12.5 |
| Antiproton | −15 | −50 |
| Antiproton | −528 | −50 |

gold[15] to fit the data with an optical model calculation.

I will quote mainly from Glassgold; the other work is similar.

He assumes a complex potential of the Woods-Saxon type

$$v(r)=\frac{V+iW}{1+\exp[(r-R)/a]},$$

plus the Coulomb potential. He chooses $R=r_0A^{\frac{1}{3}}=1.3A^{\frac{1}{3}}\times10^{-13}$ cm; $a=0.65\times10^{-13}$ cm the other constants being given in Table III. The reaction cross sections at 140 Mev agree well with the data from emulsions. The third line of Table III refers to the very deep attractive potential derived by Duerr and Teller[16] on the nuclear forces hypothesis of Duerr and Teller. This potential gives reaction cross sections which are too large, and to this extent disagrees with experiment. On similar lines we have calculated cross sections at 450 Mev trying to introduce directly the $p\bar{p}$ and $p\bar{n}$ cross sections; also there the agreement is satisfactory.

I have mentioned earlier observations on small angle scattering by complex nuclei in photographic emulsions. Goldhaber and Sandweiss[17] have analyzed the results obtained up to now with the help of the usual model of a black, absorbing disk plus Coulomb interactions. The data are still not very abundant but they agree thus far with the calculations from this model with $r(\bar{p})=1.72\times10^{-13}$ cm as obtained from the annihilation cross section.

In conclusion, I would like to express the view that we have at present the beginnings of a coherent and satisfactory picture of the large antiproton cross section: The Ball-Chew theory seems to account for the $p\bar{p}$ case and the complex nuclei are obtainable from $p\bar{p}$.

What is most needed is an extension of the extremely fragmentary experimental material, especially at lower energies.

[15] A. E. Glassgold, Phys. Rev. **110**, 220 (1958).

[16] H. P. Duerr and E. Teller, Phys. Rev. **101**, 494 (1956).

[17] G. Goldhaber and J. Sandweiss, Padova Conference (1957).