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Elastic Scattering of Antiprotons from Complex Nuclei*

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IN continuing the study of the interactions of antiprotons in nuclear emulsions, we have examined a total length of 16.0 meters of antiproton path in the energy region 50 to 200 Mev. We report here on our measurements of the elastic scattering of antiprotons in nuclear emulsion. The total path length was obtained from the various exposures to the unseparated antiproton beam[1] and from a separated-beam exposure.[2]

In these experiments, stacks of 600-micron Ilford G.5 nuclear emulsion have been exposed to antiprotons from the Berkeley Bevatron. For the purposes of the elastic-scattering measurement we have selected only tracks due to antiprotons identified by means of an annihilation star. In the range interval corresponding to 50 to 200 Mev, these tracks were carefully examined for scattering events with projected angle of scattering greater than 2°. A scattering event was accepted as elastic if there was no visible change of grain density and no visible recoil or excitation of the struck nucleus. The grain-count criterion adopted eliminates inelastic scattering events with $\Delta T_{\bar{p}}/T_{\bar{p}} \geqslant 0.2$. However, some slightly inelastic scattering events ($\Delta T_{\bar{p}}/T_{\bar{p}} < 0.2$) may still be present in our data. Scattering from free hydrogen in the emulsion and inelastic scattering from complex nuclei are discussed in a separate communication.[3]

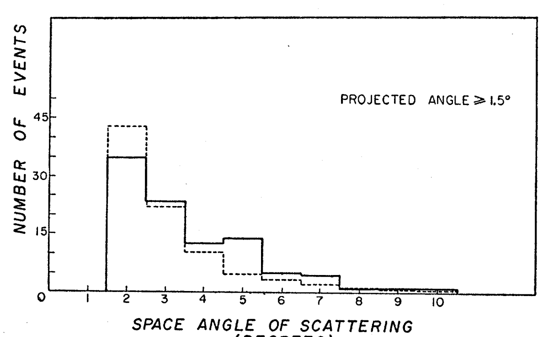

FIG. 1. Number of scattering events with projected angle greater than 1.5° as a function of the space angle of scattering. The solid histogram shows the results on 8.1 meters of antiproton track in the energy range 50 to 200 Mev, and the dashed histogram shows the distribution expected from point-nucleus Rutherford scattering.

TABLE I. Numbers of antiproton scattering events with projected angle ⩾2° observed per 30-Mev interval in a 16-meter path length in emulsion.

Space angle of scattering (degrees)	Energy interval (Mev) 50–80	80–110	110–140	140–170	170–200	Total, 50–250
2–4	18	7	11	8	7	51
4–6	6	6	6	6	3	27
6–9	4	4	4	2	2	16
9–12	3	2	1	2	2	10
12–18	1	2	1	0	0	4
18–24	0	0	2	0	0	2
24–180	0	1	0	0	0	1
2–180	32	22	25	18	14	111
Path length (cm)	146	222	310	414	508	1600

We have checked our scanning efficiency both by rescanning and by measuring a sample in which we included projected angles greater than 1.5°. In the latter case we may compare the results with point-nucleus Rutherford scattering. Figure 1 shows the results on 8.1 meters of antiproton track. For scattering events with projected angle greater than 2° the scanning efficiency is 100%. A total of 111 such scattering events were found in 16 meters of path length. Table I lists the number of antiproton scattering events for various antiproton energy intervals as well as the corresponding path-length distribution. The number of events observed in this experiment is insufficient to allow a comparison with theory in the separate energy intervals; we shall thus consider the data in the entire energy interval 50 to 200 Mev. The histogram in Fig. 2 shows the experimental angular distribution (see Table II). Of the 111 scattering events, only one occurred at an angle greater than 25°. The solid curve represents the

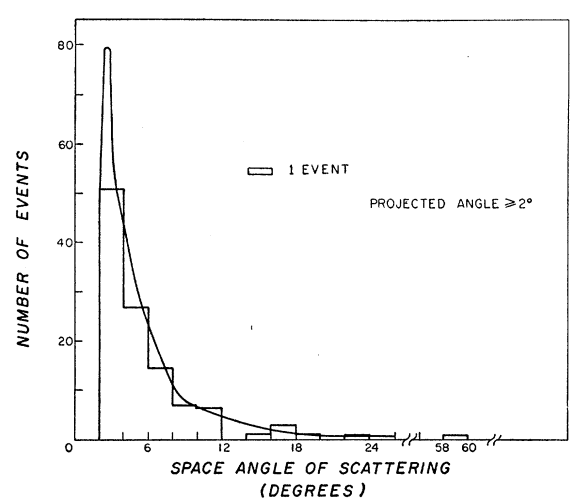

FIG. 2. The angular distribution for the entire energy interval 50 to 200 Mev. The histogram shows the observed number of elastic scattering events with projected angle greater than 2°. The solid curve shows the distribution expected from the charged-black-sphere model. Solid-angle corrections, to take account of the 2° cutoff criterion in projected angle, have been applied to the computed curve.

TABLE II. Comparison of the experimental data for elastic antiproton-nucleus scattering with calculated values for a charged-black-sphere and for point-nucleus Rutherford scattering. ($T_{\bar{p}}=50$ to 200 Mev, projected angle $\geqslant 2°$.)

Angular interval (degrees)	Number of events Experiment	Charged-black-sphere scattering[a]	Point-nucleus Rutherford scattering[a]
2–6	78	86	79
6–12	26	27	12
12–24	6	10	2.4
24–180	1	...[b]	1.2
2–180	111	...	94.6

[a] A solid-angle correction due to the 2° cutoff in projected angle has been applied to these values.
[b] The backward scattering, which rises again for this model (reference 4), has not been evaluated.

TABLE III. Comparison of experimental data for elastic antiproton-nucleus scattering of energy $T_{\bar{p}}=80$ to 200 Mev with Glassgold's calculations at $T_{\bar{p}}=140$ Mev. (Projected angle $\geqslant 2°$.)

Angular interval (degrees)	Number of events Experimental ($T_{\bar{p}}=80$ to 200 Mev)	Calculated for potential[a] $V=-15$ Mev $W=-50$ Mev	Calculated for potential[a] $V=-528$ Mev $W=-50$ Mev
2–6	54	56	71
6–12	20	17.1	24
12–24	5	4.3	10
24–180	1	1.4	9.5
2–180	80	78.8	114.5

[a] These entries were evaluated from Table IV of reference 7, and a solid-angle correction due to the 2° cutoff in projected angle has been applied. It should be noted that in Table V of reference 7 neither this correction nor the appropriate normalization factors was applied and that thus the comparison given there is not fully valid.

angular distribution expected from a "charged-black-sphere" model[4] for the antiproton-nucleus interaction. That is, we assume that all partial waves with $l \leqslant l_{\max}$ are completely absorbed, with

$$l_{\max}=\{KR[1+(2Z/137\beta KR)]^{\frac{1}{2}}-\tfrac{1}{2}\}. \quad (1)$$

The quantity R appearing in Eq. (1) is the radius of a sphere corresponding to the measured annihilation cross section as observed for nuclei in nuclear emulsions in the energy region 50 to 200 Mev. In order to deduce the value of R for the individual elements in emulsion, we have assumed an $A^{\frac{1}{3}}$ dependence for R.

Writing $R=r_0A^{\frac{1}{3}}$, we obtain $r_0=(1.64\pm0.05)\times10^{-13}$ cm. Here R is to be regarded as a measure of the number of partial waves being absorbed by the nucleus rather than as a measure of the nuclear radius. The calculated angular distribution was averaged over the energy interval considered here as well as for the elements in nuclear emulsion (excluding H)—namely, Ag, Br, C, O, and N. We do not observe a rise in the backward direction, as would be predicted[5] by the charged-black-sphere model, presumably because of reflection from the (assumed) sharp nuclear boundary. The angular distribution at forward angles, however, is not particularly sensitive to the details of the nuclear edge,[6] because of the very large absorptive contribution; thus our simplified model should be valid for small angles.

It seems likely, then, that the elastic scattering can be fitted within the accuracy of our experiment by a model in which all the elastic scattering occurs as a consequence of the strong nuclear absorption of antiprotons. This conclusion is given considerable support by the calculations of Glassgold,[7] who has made exact computations for the elastic scattering of antiprotons of 140 Mev, in nuclear emulsion, for various assumptions about the antiproton-nucleus potential. Glassgold has assumed a realistic shape for the antiproton-nucleus potential, based on recent proton-nucleus scattering data, that takes account of the diffuse nuclear boundary. He has estimated the imaginary part of the potential to be $W=-50$ Mev, corresponding to strong absorption, and has calculated the cross sections for two values of the real part of the potential V. One value, $V=-15$ Mev, was taken the same as for proton-nucleus scattering; the other value, $V=-528$ Mev, was chosen to compare with the Duerr-Teller calculations.[8,9] When these cross sections are compared with emulsion data,[2] the second choice appears to be ruled out.[10] In Table III we give a comparison of the two calculated differential cross sections with our experimental results. For this we compare our data between 80 and 200 Mev (i.e., 140$\pm$60 Mev) with his calculation carried out for 140 Mev. As can be seen from Table III, the agreement for $V=-15$ Mev is good, whereas the high potential, $V=-528$ Mev, leads to more scattering and in particular to excessive large-angle scattering. It should be noted that besides the 16 meters of path length reported here, another 22 meters has been examined for elastic scattering events with $\theta>24°$, and no additional event was found.[3] Thus the discrepancy in the interval 24° to 180° is already as high as 25 events predicted (for the potential $V=-528$ Mev) to one event found.

In all of the foregoing we have neglected the spin of the antiproton. We have studied the azimuthal dependence of the elastic scattering events and find no asymmetry. However, the antiprotons obtained in these experiments were produced at very nearly 0 degrees to the incoming proton beam, so that we would expect the polarization to be essentially zero. We have also studied the events in which the same antiproton scatters twice. For such events the antiproton can presumably be polarized in the first scattering and then be analyzed by the second scattering. To date we have observed a total of 55 pairs of two successive scattering events. Of these, in 33 cases the second scattering occurs in the same direction as the first while in 22 cases the second scattering occurs in the opposite direction. Thus so far no definite conclusion can be reached on the polarization of antiprotons by elastic scattering in nuclear emulsions.

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[5] For large angles where the Coulomb effect is small the charged-black-sphere model can be approximated by the optical model for black-sphere scattering, yielding $d\sigma/d\Omega = R^2[J_1(KR\sin\theta)/\sin\theta]^2$, which is symmetrical about 90°.

[6] See, for example, the calculations reported by R. E. Ellis and L. Schecter, Phys. Rev. **101**, 636 (1956).

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

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Conserved Currents in the Theory of Fermi Interactions*

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FEYNMAN and Gell-Mann[1] have proposed a scheme in which the vector Fermi interactions are described in terms of an interaction with itself of a vector current. In a similar way the axial vector coupling may be thought of as a self interaction of an axial vector current. Furthermore, they propose to add strangeness-violating terms to these currents in order to account for strange particle decays. In order to account for the almost precise equality of the vector coupling strengths in β decay and μ decay, Feynman and Gell-Mann suggest, in analogy with electrodynamics, that the vector (strangeness conserving) current is conserved. It is also a fact that the axial vector strengths are nearly equal for the two processes. Supposing that this equality may turn out to be precise, one might attempt to understand this in terms of a conserved axial vector current. Without here going into the subtleties associated with a precise definition of the axial vector interaction constant in such a circumstance, we shall show that such a conserved axial current can be ruled out on experimental grounds. We shall also show that a scheme involving conserved strangeness-violating currents (either vector or axial vector) can probably also be ruled out. As for the original Feynman Gell-Mann scheme concerning the conserved vector current, independent tests have been proposed by Gell-Mann.[2]

Consider first the strangeness-conserving axial vector current. Taylor[3] has made the important observation that if the conserved current ideas hold here, then $\pi\to e+\nu$ and $\pi\to\mu+\nu$ are forbidden. This is a desirable result as regards the unseen electron mode; as for the μ-meson mode, Taylor argues that perhaps the μ meson does not couple according to the scheme under discussion. We think this possibility would remove all motivation for the scheme. In any case, a consideration of β decay shows that electrons cannot couple according to the scheme. Let $j_\mu{}^A$ be the conserved current in question. The matrix element for the axial vector part of β decay would have the structure

$$M^A = i\bar{u}_e\gamma_\mu\gamma_5(1+\gamma_5)u_\nu\langle p|j_\mu{}^A|n\rangle, \qquad (1)$$

where, on general invariance grounds,[4]

$$\langle p|j_\mu{}^A|n\rangle = i\bar{u}_p\{a\gamma_\mu\gamma_5 + ib(p-n)_\mu\gamma_5\}u_n. \qquad (2)$$

The coefficients a and b are functions of $(p-n)^2$. Conservation of $j_\mu{}^A$ implies

$$(p-n)_\mu\langle p|j_\mu{}^A|n\rangle = 0; \qquad (3)$$

hence

$$b = -2ma/(p-n)^2, \qquad (4)$$

where m is the nucleon mass. From (1) and (2) we find, after carrying out reductions, that the matrix element for β decay contains an axial vector term with coefficient $g_A \equiv a$, and a *pseudoscalar* term with $g_P \equiv m_e b$, where m_e is the electron mass. From (4) it follows that

$$g_P/g_A = -2m_e m/(p-n)^2. \qquad (5)$$

This ratio is energy dependent but always very large ($\gtrsim 10^3$) and can surely be ruled out experimentally.

Let us now turn to the proposed strangeness-violating currents. Suppose all hyperons have the same parity, taken to be even. Then, as with pion decay, the occurrence of $K\to\mu+\nu$ rules out the idea of a conserved vector (axial vector) current if K is scalar (pseudoscalar). To deal with the alternate possibilities, consider the processes $K\to\pi+\mu+\nu$, $K\to\pi+e+\nu$. Depending on the K-meson parity, the matrix element is

$$M_{PS} = \bar{u}_l\gamma_\mu(1+\gamma_5)u_\nu\langle\pi|j_\mu{}^V|K\rangle, \qquad (6)$$

or

$$M_S = \bar{u}_l\gamma_\mu\gamma_5(1+\gamma_5)u_\nu\langle\pi|j_\mu{}^A|K\rangle,$$