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[4]I thank Dr. P. P. Divakaran for particularly emphasizing this point to me.

LARGE-ANGLE $\bar{p}p$ ELASTIC SCATTERING AT 3.66 GeV/c *

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The $\bar{p}p$ elastic-scattering differential cross section shows a minimum at $t\sim 0.5$ (GeV/c)^2 and a secondary maximum at $t\sim 0.9$ (GeV/c)^2. The total cross section for the annihilation process $\bar{p}+p\rightarrow\pi^-+\pi^+$ is 6.6 ± 3.5 μb; the cross section for $\bar{p}+p\rightarrow K^-+K^+$ is <2.2 μb.

A recent counter experiment[1] which measured the antiproton-proton elastic-scattering cross section at $30°<\theta_{\text{c.m.}}<90°$ for incident momenta between 1.0 and 2.5 GeV/c clearly demonstrated the presence of a minimum in the differential elastic-scattering cross section at $t\sim 0.4$ (GeV/c)^2. We report on a bubble-chamber measurement of the large-angle elastic $\bar{p}p$ scattering cross section at a laboratory momentum of 3.66 GeV/c. This exposure was taken in the 20-inch Brookhaven National Laboratory (BNL) liquid-hydrogen chamber; the Yale-BNL separated beam was used.[2]

In order to measure the large-angle $\bar{p}p$ elastic scattering distribution and to study the two-meson annihilation reactions $\bar{p}+p\rightarrow\pi^-+\pi^+$ and $\bar{p}+p\rightarrow K^-+K^+$, we conducted a special scan of approximately 50 000 frames of film. The following criteria were imposed on the two-pronged events before these events were accepted for measuring.[3]

(1) To be accepted for measurement the bubble density on the positive prong had to be less than about 5 times the minimum value. In particular, the positive track had to have at least one gap larger than 0.6 mm in space (projected length).

(2) The event had to satisfy the requirements of two-body kinematics in that at least one of the prongs had to have a projected momentum of at least 1700 MeV/c. We also required that the line of flight of the beam antiproton be straddled by the two outgoing tracks.

Our scanned sample contained approximately 20 000 two-pronged events of which we accepted 3800 for measuring. The accepted events were measured and were subsequently processed using the Yale analysis programs. The following three interpretations were considered in the analysis:

$$\bar{p}+p\rightarrow\bar{p}+p, \qquad (1)$$

$$\bar{p}+p\rightarrow\pi^-+\pi^+, \qquad (2)$$

$$\bar{p}+p\rightarrow K^-+K^+. \qquad (3)$$

There were no events found which gave acceptable fits to Reaction (3). Only three events satisfactorily satisfied the kinematics for Reaction (2). And a total of 600 events made acceptable fits to Reaction (1). There were no ambiguities found among Reactions (1), (2), and (3).[4]

At 1.61 GeV/c, Lynch et al.[1] observe cross sections of 119 ± 30 μb and 55 ± 18 μb for Reactions (2) and (3), respectively; our measured cross sections for these final states are 6.6 $\pm$ 3.5 μb and <2.2 μb.[5] This surprisingly large difference in the two-meson-annihilation cross sections may be due to contributions from resonant states in the $\bar{p}p$ system at ~2.3 GeV in the center-of-mass system.[6]

To correct our elastic-scattering data for the losses incurred as a result of the scanning criteria, we made the following assumptions: (1) The antiproton beam is unpolarized[2]; we therefore expect an isotropic distribution in the azimuthal angle of the proton about the beam

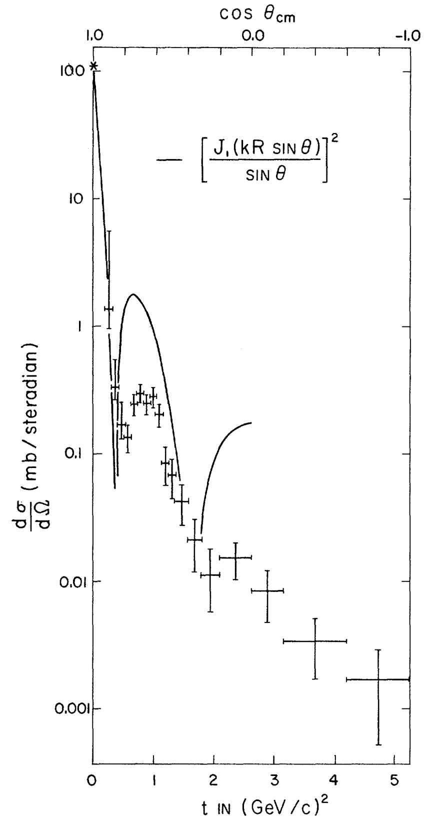

FIG. 1. Corrected angular distribution of the antiproton in the center-of-mass system. Errors include systematic effects. The smooth curve is a prediction of a black-disk diffraction model with radius $R = 1.3$ F; the curve is normalized to the optical point [see Ref. (14)].

Table I. The $\bar{p}p$ elastic-scattering cross section at 3.66 GeV/c.

Mean $\cos\theta_{\text{c.m.}}(\bar{p})$	Mean t (GeV/c)	Number of events in interval[a]	$d\sigma/d\Omega$ (μb/sr)
0.90	0.26	113 (163.5)	1430^{+4500}_{-390}
0.86	0.37	33 (38.2)	334^{+230}_{-72}
0.82	0.47	20	175^{+82}_{-39}
0.78	0.58	16	140 ± 35
0.74	0.69	29	254 ± 47
0.70	0.79	35	306 ± 52
0.66	0.90	29	254 ± 47
0.62	1.01	33	288 ± 50
0.58	1.11	24	210 ± 43
0.54	1.21	10	87.5 ± 28
0.50	1.32	8	70.0 ± 25
0.44	1.48	10	43.8 ± 14
0.36	1.69	5	21.9 ± 9
0.26	1.95	4	16.4 ± 6
0.10	2.38	9	15.8 ± 5
−0.10	2.91	5	8.8 ± 4
−0.40	3.70	4	3.5 ± 1.8
−0.80	4.76	2	1.8 ± 1.3

[a]The numbers in parentheses signify the corrected number of events in that interval of $\cos\theta_{\text{c.m.}}$ Where the entry is missing there are no corrections because of our special scanning criteria.

direction. (2) The bubbles along a track are randomly distributed.[7] (3) The bubble density is proportional to $1/\beta^2$ (β is the velocity relative to speed of light).[8] Analytically calculated[9] corrections were checked and found consistent with Monte Carlo simulations of the data.[10]

Figure 1 shows the corrected elastic-scattering distribution; we tabulate the same results in Table I. There are essentially no corrections for $t > 0.32$ (GeV/c)^2. The error bars take account of systematic[11] as well as statistical sources. The forward cross section is particularly sensitive to the parameters we use in correcting the data.[12] The outstanding feature of the experimental spectrum in Fig. 1 is the pronounced dip at $t = 0.55$ (GeV/c)^2; a similar minimum observed at lower beam energies[1] was found to occur at smaller values of t. Our data also exhibit a broad secondary maximum at $t = 0.85$ (GeV/c)^2, and a suggestion of a second minimum or shoulder at $t \sim 1.8$ (GeV/c)^2.

Minima in differential scattering cross sections have been interpreted as resulting from the vanishing of spin-flip amplitudes due to Regge-pole exchanges.[13] The Regge interpretation predicts these effects to diminish with incoming $\bar{p}$ energy. The ratio of the differential cross section at the secondary maximum to the cross section at the first minimum is 2.2 ± 0.5; hence, it appears that the relative size of the dip does not change strongly with energy.[1] It is interesting to note than a simple black-disk diffraction model,[14] with a radius of interaction of 1.3 F, predicts similar zeros in the differential cross sections.

Finally, we wish to point out that, although the evidence is not yet compelling, there appears to be a systematic change in the position of the first diffraction-peak minimum with energy[1,15]; this observation may be related to the "antishrinking" of the $\bar{p}p$ diffraction peak noted by Czyzewski et al.[2]

We thank the Yale-BNL-CCNY collaboration for allowing us to use the antiproton film for our study. The help of Miss E. Gundersheim and Dr. W. Metzger in the early stages of this experiment is gratefully acknowledged. We have used the YAP-YACK analysis system from Yale for which we thank Dr. O. Hansen and Dr. H. D. Taft. We would like to express our appreciation to the Particle Physics Group and supporting staff at Rochester for their constant encouragement and assistance. Finally, we thank Dr. H. Yuta for his comments on this work.

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[2]For a general discussion of the beam, the cross sections at this energy, and for other references, see T. Ferbel et al., Phys. Rev. 137, B1250 (1965); also see O. Czyzewski et al., Phys. Letters 15, 188 (1965).

[3]These scanning-table preselections eliminated a large amount of needless measuring and caused essentially no biases.

[4]No event gave more than one acceptable fit to the two-body hypotheses. This is not completely surprising because the reactions under study are highly overconstrained.

[5]About 1% of the total solid angle is lost for the study of the two-body annihilations when we impose our scanning criteria on the observed two-prong events. This negligible bias occurs in the region of $\cos\theta_{\text{c.m.}} \sim 0.75$ (angle of the negative meson with respect to the beam). Our annihilation results are essentially in agreement with previous work; see Ref. 2 and A. Białas and O. Czyzewski, CERN Report No. 9831/TH-486, 1964 (unpublished). The three $\pi^+\pi^-$ events have the following center-of-mass production cosines for the π^-: +0.74, +0.62, and −0.76.

[6]It is interesting that the rates for $\bar{p}p$ annihilation at rest into two charged mesons are comparable to the rates at 1.6 GeV/c. A convenient parametrization of the annihilation rates as a function of energy is the cross section relative to the total annihilation cross section: The percentage ratios of $(\pi^+ + \pi^-)$/(all annihilations) and (K^+K^-)/(all annihilations) for $\bar{p}p$ interactions at rest and at 1.61 and 3.66 GeV/c are, respectively, 0.33 ± 0.04 and 0.12 ± 0.03 [Oxford-Padua Collaboration, in Proceedings of the International Conference on Elementary Particles (Società Italiana di Fisica, Bologna, Italy, 1963), Vol. I, p. 263, and C. J. B. Hawkins, private communication]; 0.24 ± 0.05 and 0.11 ± 0.04 [G. R. Lynch et al., Phys. Rev. 131, 1287 (1963); N. H. Xuong, University of California Radiation Laboratory Report No. UCRL-10129, 1962 (unpublished)]; 0.018 ± 0.010 and <0.006 [T. Ferbel et al., Phys. Rev. 137, B1250 (1965)].

[7]W. J. Willis et al., Phys. Rev. 108, 1046 (1957).

[8]G. Blinov, I. Krestinov, and M. Lomanov, Zh. Eksperim. i Teor. Fiz. 31, 762 (1956) [translation: Soviet Phys.–JETP 4, 661 (1957)].

[9]Using assumptions (1) and (2) it can readily be shown that the probability for observing a given event in our final sample (i.e., for a track having a gap greater than d) is $1-\exp\{-mL\exp[-m(d+\delta)/\cos\lambda]\}$, where L = length of track, m = bubble density, δ = bubble diameter, d = cutoff gap size, λ = "dip" angle in bubble chamber. In our correction we further assume that planar and conical projections are equivalent, and that the effective bubble diameter is 0.3 mm.

[10]Tracks were generated by randomly populating bubbles along the particle trajectories. The probability for including these tracks in our sample was calculated and compared to that obtained using the technique described in Ref. 9; the two methods agreed to within error.

[11]We have included here the observed fluctuations in the bubble density due to the variations in the operating conditions of the bubble chamber during our run ($\lesssim$30% fluctuations). The error on the gap-size cutoff value of 0.6 mm is obtained empirically as ±0.2 mm.

[12]In a rescan of 10% of the film we used a smaller gap-size acceptance criterion of 0.3 mm; in the new events found there were none with $t > 0.32$ (GeV/c)^2.

[13]S. Frautschi, Phys. Rev. Letters 17, 722 (1966).

[14]Bruce Cork, William A. Wenzel, and Charles W. Causey, Jr., Phys. Rev. 107, 859 (1957). A radius of interaction of 1.3 F was found to fit the small-angle $\bar{p}p$ elastic-scattering data at this energy [see Ref. (2)]. We wish to point out that the simple optical model is only relevant at small angles.

[15]Although the statistics are very poor, the data for $\bar{p}p$ elastic scattering at 7 GeV/c appear to show a minimum at $t \sim 0.65$ (GeV/c)^2. We thank Professor Jack Sandweiss for a discussion of the Yale data [see J. Johnson, thesis, Yale University, 1965 (unpublished)]. The dependence of the position of the first minimum in t (t_{min}) of the center-of-mass momentum (p) can be roughly represented by $t_{\text{min}} \sim 0.3 + 0.2p$.