as well defined as G_μ. A recent discussion of this question as it relates to the universality of θ can be found in the work of Fischbach *et al.*[11]

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APPENDIX

Effect of rf modulation of the background: Assume the background, whose average value is determined to be B by the analysis program, is in fact $B + C\sin 2\pi f t$, where $f \sim 19$ MHz. The lifetime-fitting process will average this in some way characteristic of the lifetime τ. There are $2\tau f = 84$ half-cycles per lifetime, so the background counts in one lifetime might be in error by $\sim C/84$. Taking 5×10^{-4} ($\sim 5\%$ of B) as an upper limit for C, the error in the counts per lifetime could be 6×10^{-6}, which would be the order of magnitude of the error in τ.

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$\pi^- p$ Elastic Scattering near 180° from 2.15 to 6 GeV/c*

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We present differential cross-section measurements for $\pi^- p$ elastic scattering in the backward direction, with $-0.94 > \cos\theta_{\text{c.m.}} > -1.0$, for eleven beam momenta from 2.15 to 6 GeV/c.

We report here on an experiment to measure angular distributions in $\pi^- p$ elastic scattering in the very backward direction, with incident pion momenta in the range of 2 to 6 GeV/c. The purpose was to look for structure in the differential cross section possibly occurring abruptly near 180°. The existence of such structure at a momentum of 2.15 GeV/c was strongly indicated by the results of Kormanyos *et al.*,[1] who observed a dramatic dip in their 180° $\pi^- p$ elastic-scattering excitation function at that momentum. The angular distribution does drop sharply at 180° at momenta close to 2.15 GeV/c, confirmed by the results of Carroll *et al.*,[2] and preliminary results of the present experiment reported earlier.[3] This paper briefly describes our experiment, then presents and discusses the differential cross sections obtained for all of our momenta.

EXPERIMENT

The experiment was carried out at Argonne National Laboratory. It used optical spark chambers; the layout is indicated schematically in Fig. 1. A negative pion beam incident from the left traverses a 26-in.-gap spectrometer magnet, then interacts with a liquid-hydrogen target. Backscattered pions have their positions recorded by spark chambers located on both sides of the spectrometer magnet. Knowledge of the momenta of the backscattered pion and incident pion beam permits the determination of the invariant missing mass of the forward recoiling particle system. Plots of these missing-mass spectra obtained from backward π^- indicate a clear peak at the proton mass, corresponding to elastic scattering, plus an inelastic continuum which increases rapidly toward the higher missing masses.[3] The inelastic spectra for backscattered π^- and π^+ have been presented and discussed in previous publications.[4,5] Figure 1 shows spark chambers downstream of the hydrogen target; these were included to get some position information on the forward particle(s), but there was excessive sparking in these chambers and the experiment was analyzed completely on a one-arm-spectrometer basis. Not shown is a deflecting magnet located downstream before beam counters 4 and 7.

Data were obtained at eleven beam momenta: 2.15, 2.5, 2.8, 3.5, 3.95, 4.5, 5.0, 5.12, 5.25, 5.6, and 6.0 GeV/c. A total of 1.7×10^6 spark-chamber pictures were taken. The pictures at 2.15, 2.5, and 2.8 GeV/c were of rather poor quality and had to be measured with hand digitizers; film at the other momenta was successfully scanned and measured using an automatic scanning system.[6]

Two checks were available to decrease spurious background: The position of the interaction point in the hydrogen target as measured from the plan and side views had to agree within the errors; four (rather than the required three) plan-view measurements on the orbit through the magnet provided a further constraint. (Space limitations on the 35-mm film did not permit a side view of the upstream spark chambers A and B.)

Corrections were made for a variety of effects, which differed somewhat between the automatic and hand-measured film. Background was determined as follows. The fraction of spurious events contained inside the accepted "elastic" proton peak region in the missing-mass spectrum was estimated by (1) the number of kinematically forbidden backward π^+ in the same mass range (the backscattered inelastic π^- and π^+ were comparable), (2) extrapolating inward from the tails of the χ^2 distributions from the origin and orbit fits. For the automatically scanned film, methods (1) and (2) averaged 4.7% and 8%, respectively, in reasonable agreement, and $(6.3\pm1.6)\%$ was taken as the background estimate. An angular dependence was observed and included in the background subtraction. For the hand-measured film the two methods combined to give $(3.1\pm1.5)\%$ background, with an estimated angular variation within ±2% of the average cross section. Other major corrections to the data resulted from decay of the backscattered π^- [averaging $(9\pm2)\%$], strong interactions of the backscattered π^- [averaging $(6\pm3)\%$], μ^-, e^- contamination of the π^- beam [$(6\pm2)\%$], and chamber inefficiency, which is discussed below.

For the automatically measured film the event loss from spark-chamber inefficiency (or track-recognition inefficiency) varied from 3% to 14%, averaged $(8\pm4)\%$; this chamber inefficiency could be estimated from the observed yields by using the number of sparks per track as a measure of film quality. Comparisons of hand-measured and automatically measured film samples also gave similar results. From these comparisons we estimate that possible angular biases from this effect are within ±9%. (No angular correction was made.) An additional loss from apparent spark mergings in the side view was $(4.7\pm3)\%$. We obtain for the automatically scanned film a resultant over-all normalization uncertainty of ±8% at each momentum and a relative uncertainty of ±5% between different momenta, in addition to the statistical errors and background subtraction errors

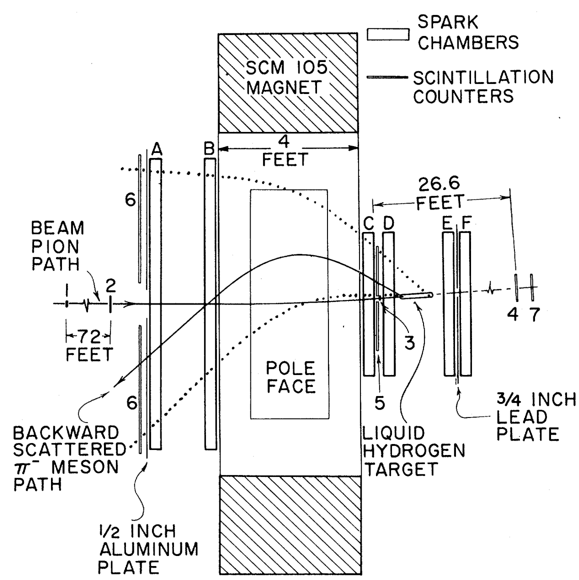

FIG. 1. Schematic layout of the experiment. The dotted lines indicate the limiting trajectories for accepted back-scattered π^-.

discussed above.

For the hand-scanned film the over-all correction for efficiency loss was (6 ± 2)%, determined from double scanning. The angle-dependent efficiency correction varied from 1% at 180° to 18% away from 180°, with an estimated uncertainty of ±5%. The over-all normalization uncertainty is ±7%, momentum to momentum ±3%.

RESULTS AND DISCUSSION

Our differential cross sections are presented in Tables I and II. The Table I data, 2.15 to 2.8 GeV/c, are from the hand-measured film, the Table II data, 3.5 to 6 GeV/c, from automatically measured film; the errors were somewhat different in the two cases as indicated above and in the notes

TABLE I. Differential cross sections for π^-p backward elastic scattering at 2.15 to 2.80 GeV/c.[a,b]

P_{beam} (GeV/c)	$-\cos\theta$	$\frac{1}{2}\Delta\cos\theta$	$d\sigma/d\Omega$ (μb/sr)	No. of events	u [(GeV/c)^2]	$\frac{1}{2}\Delta u$ [(GeV/c)^2]	$d\sigma/du$ [μb/(GeV/c)^2]	$-t$ [(GeV/c)^2]
2.15	0.9980	0.0010	8.43 ± 3.44	6	0.147	0.0016	32.18 ± 13.14	3.290
	0.9960	0.0010	10.94 ± 4.47	6	0.143	0.0016	41.75 ± 17.05	3.287
	0.9925	0.0025	20.36 ± 4.67	19	0.138	0.0041	77.68 ± 17.82	3.281
	0.9875	0.0025	32.91 ± 7.02	22	0.129	0.0041	125.60 ± 26.78	3.273
	0.9825	0.0025	37.21 ± 7.93	22	0.121	0.0041	141.99 ± 30.27	3.264
	0.9775	0.0025	50.93 ± 9.62	28	0.113	0.0041	194.33 ± 36.72	3.256
	0.9725	0.0025	44.69 ± 9.53	22	0.105	0.0041	170.52 ± 36.35	3.248
	0.9675	0.0025	64.74 ± 12.02	29	0.096	0.0041	247.05 ± 45.88	3.240
	0.9625	0.0025	82.88 ± 14.21	34	0.088	0.0041	316.28 ± 54.24	3.231
	0.9575	0.0025	52.79 ± 11.80	20	0.080	0.0041	201.44 ± 45.04	3.223
	0.9525	0.0025	85.36 ± 15.85	29	0.072	0.0041	325.74 ± 60.49	3.215
	0.9475	0.0025	46.80 ± 14.80	10	0.063	0.0041	178.60 ± 56.48	3.207
2.50	0.9980	0.0010	32.15 ± 5.51	34	0.128	0.0020	102.76 ± 17.62	3.927
	0.9960	0.0010	32.49 ± 6.50	25	0.124	0.0020	103.87 ± 20.77	3.923
	0.9925	0.0025	36.38 ± 5.36	46	0.118	0.0049	116.29 ± 17.15	3.916
	0.9875	0.0025	38.24 ± 6.29	37	0.108	0.0049	122.25 ± 20.10	3.907
	0.9825	0.0025	30.32 ± 5.83	27	0.098	0.0049	96.92 ± 18.65	3.897
	0.9775	0.0025	56.15 ± 8.47	44	0.088	0.0049	179.49 ± 27.06	3.887
	0.9725	0.0025	48.23 ± 8.27	34	0.078	0.0049	154.19 ± 26.44	3.877
	0.9675	0.0025	67.01 ± 10.22	43	0.068	0.0049	214.21 ± 32.67	3.867
	0.9625	0.0025	34.09 ± 7.62	20	0.059	0.0049	108.96 ± 24.36	3.857
	0.9575	0.0025	41.25 ± 9.72	18	0.049	0.0049	131.87 ± 31.06	3.848
	0.9525	0.0025	50.36 ± 17.80	8	0.039	0.0049	160.98 ± 56.91	3.838
2.80	0.9980	0.0010	47.63 ± 7.26	43	0.116	0.0022	133.57 ± 20.37	4.477
	0.9960	0.0010	39.82 ± 7.96	25	0.111	0.0022	111.67 ± 22.33	4.472
	0.9925	0.0025	39.24 ± 6.20	40	0.103	0.0056	110.04 ± 17.40	4.464
	0.9875	0.0025	26.50 ± 5.65	22	0.092	0.0056	74.31 ± 15.84	4.453
	0.9825	0.0025	34.27 ± 6.85	25	0.081	0.0056	96.10 ± 19.22	4.442
	0.9775	0.0025	26.64 ± 6.46	17	0.070	0.0056	74.69 ± 18.12	4.431
	0.9725	0.0025	20.97 ± 6.05	12	0.059	0.0056	58.81 ± 16.98	4.420
	0.9675	0.0025	17.42 ± 5.81	9	0.047	0.0056	48.85 ± 16.28	4.408
	0.9625	0.0025	16.25 ± 6.64	6	0.036	0.0056	45.58 ± 18.61	4.397

[a] The variables θ and Ω are in the center-of-mass frame.

[b] The stated errors are statistical only. There is an additional normalization uncertainty of ±7%, an angle-dependent efficiency uncertainty of ±5%, and an angle-dependent background-subtraction uncertainty of ±2% of the average cross section at each energy.

to the tables. Our results are presented in graphical form in Fig. 2,[7-14] along with data from other experiments for comparison. The momentum dependence of the cross section at exactly 180° is available from the work of Kormanyos *et al.*; it is shown in Fig. 3, as well as being plotted on Fig. 2. As indicated above, the dip in the 180° excitation function at 2.15 GeV/c has a clearly associated dip at 180° in the angular distribution at that momentum. This dip disappears by 2.5 GeV/c, and there is a sharp backward peak by 2.8 GeV/c. Figure 4 indicates the general behavior of the cross section over our momentum range; the lines are hand-drawn through the data of the groups listed in Fig. 2; note that our data contribute only in the very backward direction, for $u > 0$. It is evident from Fig. 4 that the sharp backward peak around 2.8 GeV/c is being generated by a cross section holding nearly constant at 180°, but falling rapidly away from 180° with increasing momentum. Not until 3.55 GeV/c does the very backward cross section $d\sigma/du \sim e^{Bu}$ have a slope as low as $B \sim 4$, characteristic of higher momenta.[14-16] A very nice fit to these rapidly varying cross sections has been made by Crittenden *et al.*,[7] using only direct-channel resonances, over the range 2.18 to 3 GeV/c.

In Fig. 5 we present the energy dependence of the differential cross section at a fixed value of $u = 0.04$ (GeV/c)^2 (away from 180°), generally well inside our range. Our cross sections at this u were determined using simple straight-line fits to the data of Tables I and II. The cross sections shown from other experiments[2,7,10,12,14-17] were obtained by interpolating or fitting the published data. A question of interest here is: To how low a momentum are the fixed-u data consistent with a power-law dependence on s, $d\sigma/du \sim s^b$, a parametrization suggested by Regge-exchange theory.[18] It is evident from Fig. 5 that in the resonance region below ~2.5 to 3 GeV/c the data do not agree with such a smooth energy dependence; models in this region have had to include resonance effects.[19] Above ~6 GeV/c both $\pi^+ p$ and $\pi^- p$ backward elastic

TABLE II. Differential cross sections for $\pi^- p$ backward elastic scattering at 3.5–6.0 GeV/c.[a,b]

P_{beam} (GeV/c)	$-\cos\theta$	$\frac{1}{2}\Delta\cos\theta$	$d\sigma/d\Omega$ (μb/sr)	No. of events	u [(GeV/c)^2]	$\frac{1}{2}\Delta u$ [(GeV/c)^2]	$d\sigma/du$ [μb/(GeV/c)^2]	$-t$ [(GeV/c)^2]
3.50	0.9973	0.0022	12.04 ± 2.27	36	0.091	0.0065	26.20 ± 4.95	5.764
	0.9900	0.0050	13.96 ± 2.22	45	0.070	0.0144	30.39 ± 4.83	5.744
	0.9775	0.0075	10.27 ± 1.86	33	0.034	0.0216	22.35 ± 4.04	5.707
3.95	0.9973	0.0022	9.00 ± 2.03	26	0.080	0.0074	17.11 ± 3.85	6.597
	0.9900	0.0050	10.36 ± 1.96	32	0.056	0.0165	19.71 ± 3.73	6.573
	0.9775	0.0075	9.77 ± 2.01	25	0.015	0.0248	18.59 ± 3.82	6.532
4.50	0.9973	0.0022	7.46 ± 1.85	21	0.069	0.0086	12.28 ± 3.05	7.617
	0.9900	0.0050	8.91 ± 1.81	27	0.041	0.0191	14.67 ± 2.98	7.590
	0.9775	0.0075	11.16 ± 2.50	20	−0.007	0.0286	18.38 ± 4.11	7.542
5.00	0.9977	0.0017	8.10 ± 2.38	14	0.062	0.0075	11.89 ± 3.49	8.549
	0.9930	0.0030	4.26 ± 1.84	7	0.042	0.0128	6.26 ± 2.71	8.529
	0.9850	0.0050	3.27 ± 1.46	6	0.008	0.0214	4.80 ± 2.14	8.494
5.12	0.9977	0.0017	9.05 ± 2.28	19	0.061	0.0077	12.95 ± 3.26	8.772
	0.9930	0.0030	5.00 ± 1.81	10	0.040	0.0132	7.15 ± 2.59	8.751
	0.9850	0.0050	5.06 ± 1.64	11	0.005	0.0220	7.24 ± 2.35	8.716
5.25	0.9977	0.0017	3.35 ± 1.64	7	0.059	0.0079	4.67 ± 2.29	9.014
	0.9930	0.0030	6.96 ± 2.18	12	0.037	0.0135	9.69 ± 3.04	8.993
	0.9850	0.0050	5.90 ± 1.87	11	0.001	0.0226	8.21 ± 2.61	8.957
5.60	0.9977	0.0017	5.38 ± 1.93	10	0.054	0.0085	6.98 ± 2.51	9.666
	0.9930	0.0030	7.21 ± 2.21	12	0.031	0.0145	9.36 ± 2.86	9.643
	0.9850	0.0050	4.84 ± 1.80	8	−0.008	0.0242	6.28 ± 2.34	9.604
6.00	0.9977	0.0017	3.78 ± 1.03	18	0.049	0.0091	4.56 ± 1.24	10.412
	0.9930	0.0030	5.17 ± 1.17	22	0.024	0.0156	6.24 ± 1.42	10.387
	0.9850	0.0050	2.70 ± 0.93	10	−0.017	0.0261	3.26 ± 1.12	10.345

[a] The variables θ and Ω are in the center-of-mass frame.

[b] The stated errors include both statistical errors and estimated errors from background subtraction. There is an additional normalization uncertainty of ±8% and an angle-dependent efficiency uncertainty of ±9%.

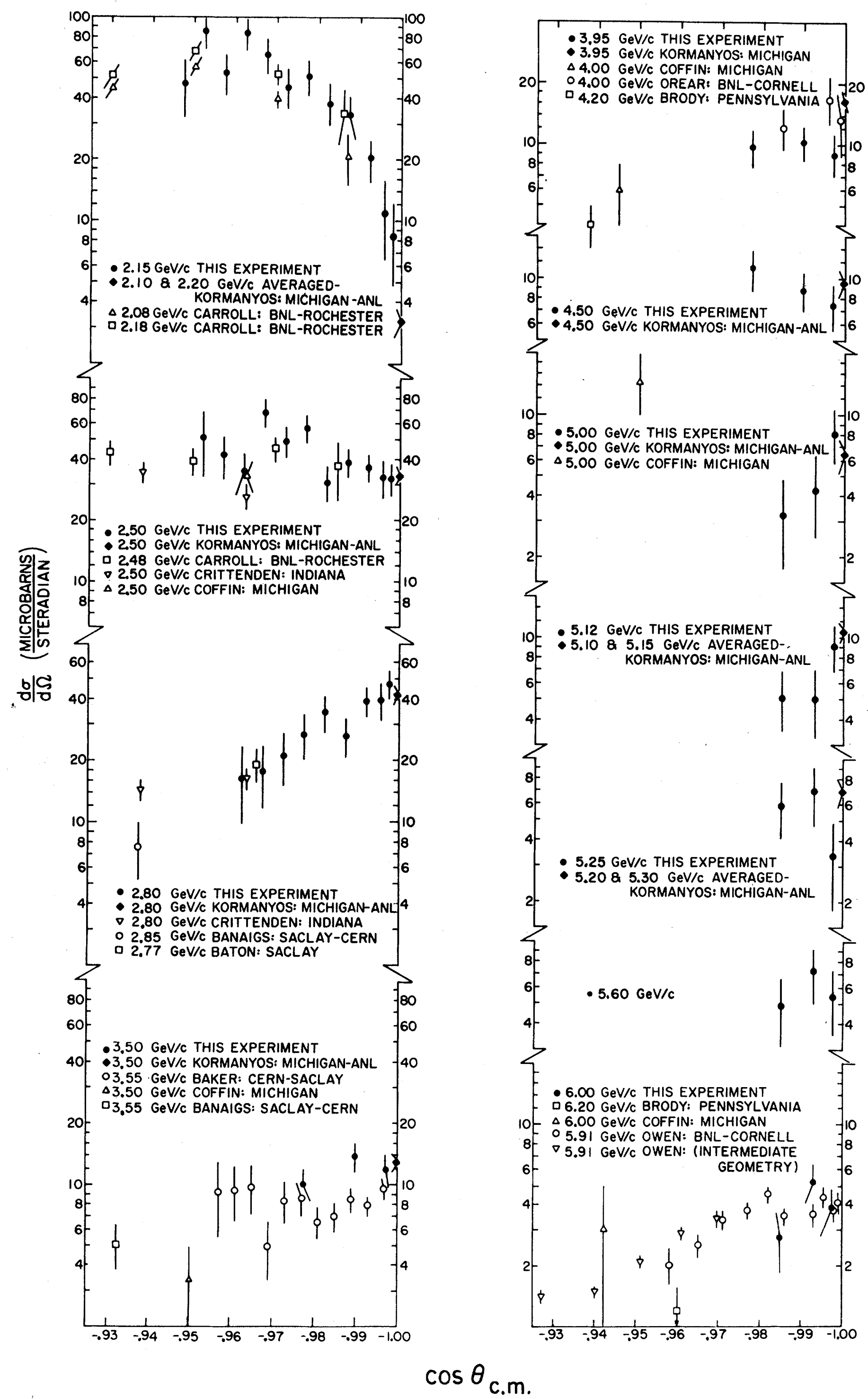

FIG. 2. Differential cross section in the center-of-mass frame for backward $\pi^- p$ elastic scattering. References for the other experiments: Kormanyos, Ref. 1; Carroll, Ref. 2; Crittenden, Ref. 7; Coffin, Ref. 8; Banaigs, Ref. 9; Baton, Ref. 10; Baker, Ref. 11; Orear, Ref. 12; Brody, Ref. 13; Owen, Ref. 14.

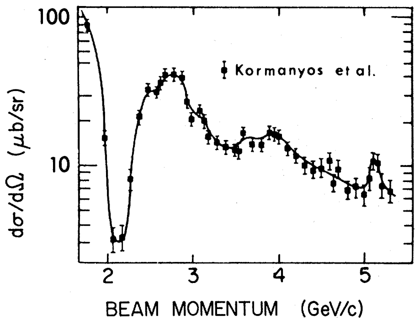

FIG. 3. Differential cross section in the center-of-mass frame for 180° $\pi^- p$ elastic scattering as a function of π^- beam momentum, from Ref. 1.

scattering data have been fitted well with pure Regge baryon exchange.[20] A simple power-law dependence is a good fit to the higher-momentum data of Fig. 5: Taking the data from 5.91 to 16.25 GeV/c we find a value of $b = -1.98 \pm 0.1$, with a confidence level for the fit of 61%. This value of b can be compared with the approximate value expected for pure Δ_δ exchange in the Regge model[18,20]; using $b = 2\alpha(u) - 2$ we obtain $b = -1.62$ at $u = 0.04$. Now considering lower momenta alone, the range from 2.77 to 6 GeV/c of Fig. 5 is fitted with a slope $b = -2.86 \pm 0.17$, confidence level 20%, a considerably higher value of b. (Our data alone over the same range give $b = -3.14 \pm 0.24$, confidence level 80%.) A fit over the larger momentum range 2.77 to 16.25 GeV/c yields $b = -2.34 \pm 0.1$ with a confidence level of 0.5%. (Increasing the lower momentum bound of the range would of course rapidly increase the confidence level of the over-all fit.) It is apparent that the strongest statement one can make from the above is that there is an indication of an increasing energy dependence below 6 GeV/c and the effects of resonances should not be ignored.

The work of Kormanyos *et al.*[1] indicated the possible presence of a resonance bump at 5.12 GeV/c (see Fig. 3). We estimate that the statistical significance of their result is around two standard deviations (~4% confidence level). We obtained data at three momenta in the region of that peak, 5.0, 5.12, and 5.25 GeV/c, but it is evident from Fig. 2 that our statistics do not permit a clear confirmation or refutation of a sharp peak at 180°; however, it should be noted that a peak of the size suggested by their bump which extended completely over our angular range would be somewhat difficult to reconcile with our 5.12-GeV/c data.

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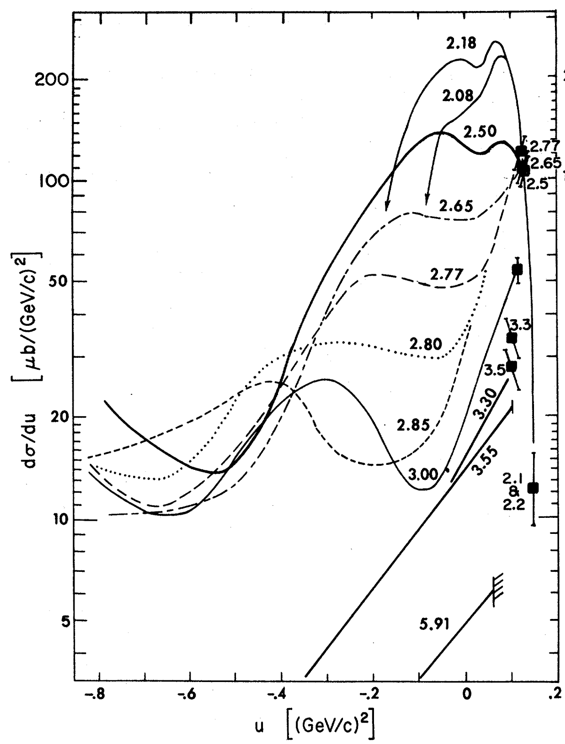

FIG. 4. Graphical summary of the backward $\pi^- p$ elastic scattering cross section, 2–6 GeV/c. The lines are hand-drawn through data from experiments referred to in Fig. 2. The plotted points are at 180°, from Ref. 1.

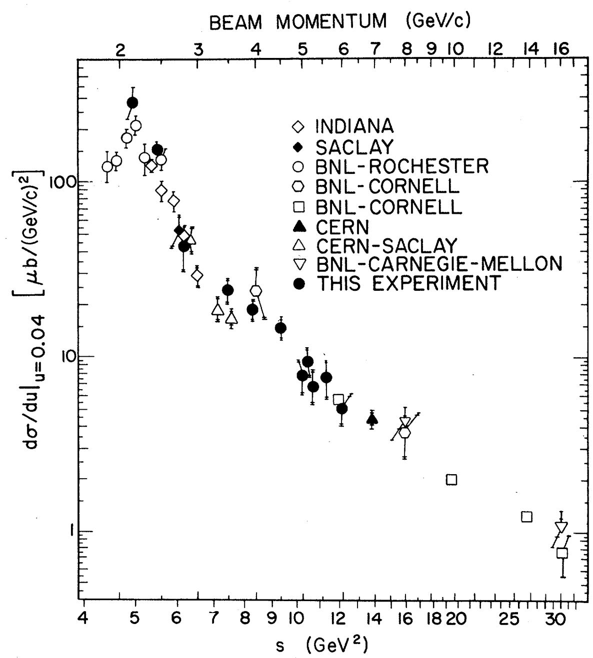

FIG. 5. Energy dependence of the differential cross section for $\pi^- p$ elastic scattering at $u = 0.04$ (GeV/c)^2. The outer error bars include normalization as well as statistical errors. The data of other experiments are from Refs. (in order) 7, 10, 2, 12, 14, 15, 17, and 16.

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