by collisional ionization. Thus, the effective cross section for producing a given line does not continue to rise as one proceeds to lower energies. Most of the contribution to a given line comes from a fairly narrow range of energies around ~2 MeV.

Recently, evidence for a galactic component of the diffuse x-ray background in the 1.4- to 18-keV band has been reported.[19] Although the detector is inadequate to resolve lines from this flux, the data below ~2 keV can perhaps be explained by unresolved Mg α and Si α lines. However, the reported flux in the 2- to 18-keV band exceeds our predicted flux by a factor of ~5. Due to the lower abundances of the heavier cosmic-ray nuclei the flux from lines above ~2 keV is quite small.

We would like to thank Dr. G. B. Field, Dr. M. J. Rees, and Dr. M. W. Werner for helpful comments on this work.

[1]S. Hayakawa, Publ. Astron. Soc. Japan 12, 110 (1960).

[2]S. Hayakawa, S. Nishimura, and K. Takayanagi, Publ. Astron. Soc. Japan 13, 184 (1961).

[3]S. B. Pikel'ner, Astron. Zh. 44, 915 (1967) [translation: Soviet Astron.—AJ 11, 737 (1968)].

[4]V. K. Balasubrahmanyan, E. Boldt, R. A. R. Palmeira, and G. Sandri, Can. J. Phys. 46, 5633 (1968).

[5]L. Spitzer and M. G. Tomasko, Astrophys. J. 152, 971 (1968).

[6]J. Silk and M. W. Werner, to be published.

[7]G. Gloeckler and J. R. Jokipii, Astrophys. J. 148, 241 (1967).

[8]G. B. Field, D. W. Goldsmith, and H. J. Habing, Astrophys. J. 155, L149 (1969). The flux of 2-MeV cosmic rays used by these authors is about half that assumed in Ref. 5, as heavy nuclei were included. This increases the heat input of a given flux of low-energy cosmic rays at 2 MeV/nucleon by a factor $(N_Z/N_H)_{CR}Z^2$.

[9]D. W. Greenberg, Astrophys. J. 155, 451 (1969).

[10]S. Hayakawa and M. Matsuoka, Progr. Theoret. Phys. (Kyoto) Suppl. 30, 204 (1964).

[11]E. Boldt and P. Serlemitsos, paper presented at 128th Meeting of American Astrononical Society, Austin, Texas, December, 1968 (unpublished).

[12]R. J. Gould and G. R. Burbidge, Astrophys. J. 138, 969 (1963).

[13]H. A. Bethe and E. E. Salpeter, Quantum Mechanics of One- and Two-Electron Atoms (Springer-Verlag, Berlin, Germany, 1957), Sec. IVa.

[14]D. R. Bates and A. Dalgarno, Proc. Phys. Soc. (London) A66, 972 (1953).

[15]J. R. Hiskes, Phys. Rev. 137, A361 (1965).

[16]Th. Schmidt-Kaler, in Radio Astronomy and the Galactic System, edited by H. van Woerden (Academic Press, Inc., New York, 1967), p. 172.

[17]C. M. Comstock, C. Y. Fan, and J. A. Simpson, Astrophys. J. 155, 609 (1969).

[18]K. L. Bell and A. E. Kingston, Monthly Notices Roy. Astron. Soc. 136, 241 (1967).

[19]B. A. Cooke, R. E. Griffiths, and K. A. Pounds, to be published.

π^-p ELASTIC SCATTERING AT 2.51, 2.76, AND 3.01 GeV/c NEAR $t \simeq -3$ (GeV/c)^2*

M. Fellinger, E. Gutman, R. C. Lamb, F. C. Peterson, and L. S. Schroeder
Institute for Atomic Research and Department of Physics, Iowa State University, Ames, Iowa 50010

and

R. C. Chase, E. Coleman, and T. G. Rhoades
School of Physics, University of Minnesota, Minneapolis, Minnesota 55455
(Received 30 July 1969)

Differential cross sections for the elastic scattering of negative pions from hydrogen have been measured over a limited range of squared four-momentum transfer (t) in the vicinity of $t \simeq -3$ (GeV/c)^2 for incident pion momenta of 2.51, 2.76, and 3.01 GeV/c. These measurements confirm the existence of a minimum in the differential cross section in this region of incident momentum and scattering angle. The minimum occurs at a smaller value of t [$t \simeq -2.6$ (GeV/c)^2] than has been observed at higher momenta.

Previous measurements of π^-p elastic scattering at 5.90 GeV/c clearly show a minimum in the differential cross section at a squared value of four-momentum transfer (t) of $t \simeq -3$ (GeV/c)^2.[1] These measurements stimulated the observation[2] that this same structure exists at a similar value of t in lower momenta measurements.[3,4] Many two-body particle reactions at high incident momenta are characterized by differential cross sections which have structure as a function of the kinematic variables.[5] Various models have been proposed to interpret these structures[6]; for some reactions, considerable progress has been made.[7] In attempting to understand π^-p elastic scattering near $t \simeq -3$ $(\text{GeV}/c)^2$, the lack of precise data has been a serious constraint on the theoretical work.

This paper presents the results of an experiment performed at the Argonne National Laboratory zero-gradient synchrotron to measure this structure with precision near 2.5-GeV/c incident momentum. The apparatus initially was designed to measure the differential cross section for the elastic scattering of negative pions from deuterons. A description of the apparatus has been published with these primary measurements.[8] The elastic events were detected by a double arm spectrometer consisting of two bending magnets and three scintillation counter arrays. For the present measurements, the target was filled with liquid hydrogen and the magnet polarities were reversed from those of Ref. 8. Appropriate adjustments of the positions and timing of the scintillation counters were also made.

The differential cross sections and various corrections were calculated as described in Ref. 8. The results are listed in Table I. The errors given are statistical errors associated with event counts only. There is an additional overall uncertainty of ±7% to be associated with all data points.

The results at 2.51, 2.76, and 3.01 GeV/c from the present experiment are shown in Fig. 1 along with some previous results at 3.0 and 5.90 GeV/c.[1,3] Although not shown, previous results at 2.5 GeV/c are in reasonable agreement with the present results at 2.51 GeV/c.[3] Note that the well-defined minimum in the 2.51-GeV/c data is located at $|t| \simeq 2.6$ $(\text{GeV}/c)^2$, while, as previously stated, the 5.90-GeV/c results of Ref. 1 show a minimum centered at $|t| \simeq 3.0$ $(\text{GeV}/c)^2$. In addition, the present results at 3.01 GeV/c and the 3.0-GeV/c data of Ref. 3 indicate the existence of a minimum at $t \simeq -2.8$ $(\text{GeV}/c)^2$. Thus, the position of the minimum moves to larger values of $|t|$ as the momentum increases. Note that as the momentum varies from 2.5 to 5.90 GeV/c, the value of $|t|$ at the minimum increases at most by ~15% while the cross section in the region of the minimum decreases by over a factor of 100.

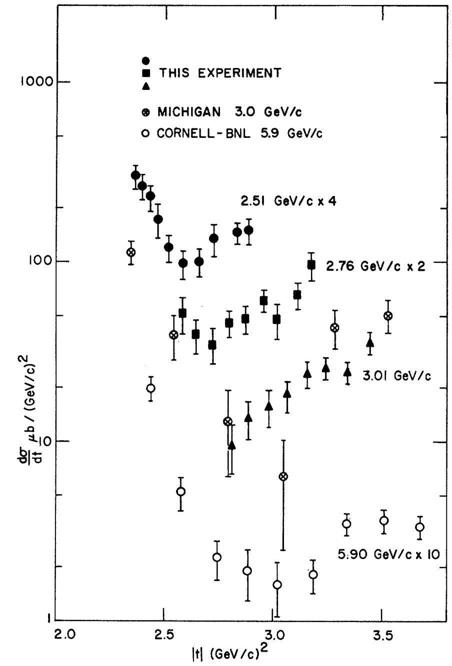

FIG. 1. $\pi^- p$ differential cross sections at 2.51, 2.76, and 3.01 GeV/c from the present experiment, at 3.0 GeV/c from Ref. 3, and at 5.90 GeV/c from Ref. 1. The 2.51-, 2.76-, and 5.90-GeV/c data are multiplied by factors of 4, 2, and 10, respectively, for the purpose of illustration.

Table I. $\pi^- p$ elastic scattering.

$-t$ $(\text{GeV}/c)^2$	$d\sigma/dt$ μb/$(\text{GeV}/c)^2$	Statistical error μb/$(\text{GeV}/c)^2$	$-t$ $(\text{GeV}/c)^2$	$d\sigma/dt$ μb/$(\text{GeV}/c)^2$	Statistical error μb/$(\text{GeV}/c)^2$	$-t$ $(\text{GeV}/c)^2$	$d\sigma/dt$ μb/$(\text{GeV}/c)^2$	Statistical error μb/$(\text{GeV}/c)^2$
	2.51 GeV/c			2.76 GeV/c			3.01 GeV/c	
2.371	58.1	8.7	2.585	20.2	4.8	2.812	7.4	2.3
2.404	51.8	8.1	2.642	15.4	3.4	2.895	10.5	2.5
2.439	44.7	7.3	2.718	13.6	3.2	2.980	12.1	2.8
2.473	33.4	6.9	2.796	17.8	3.0	3.065	14.1	2.7
2.524	23.5	3.9	2.873	18.8	3.2	3.156	18.5	3.2
2.593	19.2	3.5	2.954	23.9	3.3	3.244	19.9	2.8
2.663	19.7	3.5	3.012	18.6	4.1	3.376	18.9	2.8
2.730	26.2	5.3	3.108	25.5	4.2	3.443	27.5	4.1
2.837	28.3	3.6	3.173	37.1	6.8			
2.889	29.3	4.7						

It is also evident from Fig. 1 that the differential cross section decreases more rapidly with momentum in the region $|t| \gtrsim |t_{min}|$ than in the region $|t| \lesssim |t_{min}|$, where t_{min} is the value of t at the minimum. This variation of the momentum dependence may in fact be the most interesting feature of the cross section to study since, in some sense, it could be the "cause" of the momentum dependence of t_{min}. For example, assume that the cross section in the region of t_{min} can be described in terms of two amplitudes, the dominant one for $|t| < |t_{min}|$ having a small momentum dependence and the dominant one for $|t| > |t_{min}|$ having a large momentum dependence. The minimum could then be interpreted as an interference effect at the value of t where these amplitudes have a comparable magnitude. This description implies that $|t_{min}|$ increases with increasing momentum.

The present results, while not conclusive, do not favor diffraction models since most models of this type predict that the minimum should move to smaller $|t|$ with increasing momentum.[6] Regge models can predict a minimum in a differential cross section when an exchange amplitude has a kinematic or dynamic zero. Such a minimum, while positioned roughly at constant t, can be expected to move slightly to larger $|t|$ with increasing energy.[9]

The present results are unfavorable to the suggestion of Booth that this minimum is, in some sense, the same effect which is evident in the 180° $\pi^- p$ differential cross section.[2] While the present data at 2.51 GeV/c show a minimum at $|t| \simeq 2.6$ (GeV/c)^2, the data of Kormanyos et al.[10] place the minimum in the 180° cross section at $|t| \simeq 3.3$ (GeV/c)^2.

We again thank all those who have helped us in this work, in particular the zero-gradient synchrotron personnel at Argonne National Laboratory.

---

*Work supported in part by the Ames Laboratory of the U. S. Atomic Energy Commission and the National Aeronautics and Space Administration.

[1]A. Ashmore, C. J. S. Damerell, W. R. Frisken, R. Rubinstein, J. Orear, D. P. Owen, F. C. Peterson, A. L. Read, D. G. Ryan, and D. H. White, Phys. Rev. Letters 21, 387 (1968), and Phys. Letters 28B, 61 (1968); D. P. Owen et al., Phys. Rev. 181, 1794 (1969).

[2]N. E. Booth, Phys. Rev. Letters 21, 465 (1968).

[3]C. J. Coffin, N. Dikmen, L. Ettlinger, D. Meyer, A. Saulys, K. Terwilliger, and D. Williams, Phys. Rev. 159, 1169 (1967).

[4]W. Busza, B. G. Duff, D. A. Garbutt, F. F. Heymann, C. C. Nimmon, K. M. Potter, T. P. Swetman, E. H. Bellamy, T. F. Buckley, R. W. Dobinson, P. V. March, J. A. Strong, and R. N. F. Walker, Phys. Rev. 180, 1339 (1969).

[5]P. K. Williams, D. M. LeVine, and J. H. Koschik, "References and Some Two-Body Data for High Energy Reactions," University of Michigan (unpublished).

[6]See, for example, Chan H.-M., in Proceedings of the Fourteenth International Conference on High-Energy Physics, Vienna, Austria, 1968, edited by J. Prentki and J. Steinberger (CERN Scientific Information Service, Geneva, Switzerland, 1968), p. 391.

[7]For example, $\pi^- p \to \pi^0 n$ as described by F. Arbab and C. Chiu, Phys. Rev. 147, 1045 (1966).

[8]M. Fellinger, E. Gutman, R. C. Lamb, F. C. Peterson, L. S. Schroeder, R. C. Chase, E. Coleman, and T. G. Rhoades, Phys. Rev. Letters 22, 1265 (1969).

[9]V. Barger, in Proceedings of the Topical Conference on High Energy Collisions of Hadrons, CERN, January, 1968 (CERN Scientific Information Service, Geneva, Switzerland, 1968), Vol. I, p. 3.

[10]S. W. Kormanyos, A. D. Krisch, J. R. O'Fallon, K. Ruddick, and L. G. Ratner, Phys. Rev. Letters 16, 709 (1966), and Phys. Rev. 164, 1661 (1967).