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Evidence for coherent effects in large-angle hadron-hadron scattering*

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We suggest, by looking at pp and π^+p elastic data, that the evidence for the parton prediction $d\sigma/dt \sim s^{-n}f(\theta)$ is not as convincing as is generally supposed. We also draw attention to the presence of well-defined structures in $(d\sigma/dt)_\theta$; these may well reveal a strong component of conventional coherent scattering effects, even at large angles.

It is usually assumed that in hadron-hadron scattering at large angles ($\theta_{\text{c.m.}} \sim 90°$), conventional coherent effects (such as, say, diffraction) are small, and that scattering at these angles is dominated by collisions between the constituent partons. Several parton theories[1] have recently been developed to describe large-angle scattering, one of the most interesting predictions here being that $d\sigma/dt \sim s^{-n}f(\theta)$, where n depends upon the particular model and the particular particles involved in the reaction. It is generally claimed[1] that the experimental data support this prediction.

In the present paper we examine in detail fixed-angle differential cross sections for pp and π^+p elastic scattering (where the data are most plentiful), and make the following observations: (1) The prediction $d\sigma/dt \sim s^{-n}f(\theta)$ is not well satisfied. (2) The data in fact contain some well-defined fine structure (some of which has been known for years). (3) We replot the $(d\sigma/dt)_\theta$ data in a way which strongly indicates the origin of this structure. (4) We conclude that there are substantial coherent-scattering effects present even at large angles.

$(d\sigma/dt)_\theta$ vs ln$s$ PLOTS

In Fig. 1(a), we have plotted $(d\sigma/dt)_\theta$ vs ln$s$ for pp elastic scattering[2] at fixed angles $\theta = 60°$, $70°$, $80°$, and $90°$, and in Fig. 1(b) the corresponding data for π^+p elastic scattering[3] at $\theta = 60°$, $90°$, and $120°$. Because of beam intensity, the pp data are considerably more accurate and more plentiful. The following features seem fairly evident *from the data:*

(a) Neither the pp nor the π^+p data follow straight lines (even if one considers only the last few points). Thus $(d\sigma/dt)_\theta$ does not go as a simple power s^{-n}.

(b) For pp, the general trend of the data is such that rough lines through the data are convex up. This indicates that $(d\sigma/dt)_\theta$ goes slightly faster than a fixed power. Moreover, for different angles θ, these rough lines are not parallel. Thus, the factorization of the s and θ dependence in $d\sigma/dt$ is only rather approximate.

(c) The fixed-angle differential cross sections for both pp and π^+p are in fact very *rich in structure.* The π^+p data have distinct dips, while the pp data (which also go out to much higher energies) seem to possess a sequence of reasonably well-defined breaks (with convex-up sections between). We have drawn lines in Figs. 1(a) and 1(b), to indicate where these breaks seem to occur.[4]

These observations are quite different from those which have been made in the past. However, previous plots of the data do of course contain the curvature and the structure mentioned here (though not easily seen sometimes because of the compressed logarithmic scales used), but these features seem to have been ignored. We take the point of view that these features are presumably telling us about some *reasonably strong component that is present in scattering at large angles.* It seems important therefore, in view of the present interest in large-angle and large-$p_\perp$ scattering in elastic and inclusive processes, to try to determine the origin of this structure. In particular, what is the correlation between the succession of breaks in $(d\sigma/dt)_\theta$ for a given fixed θ, and what is the correlation between corresponding breaks for different θ's?

$(d\sigma/dt)_\theta$ vs t PLOTS

It will be noted from Fig. 1 that corresponding breaks in $(d\sigma/dt)_\theta$ drift in ln$s$ as θ is changed from one value to another. This suggests that perhaps there is another variable where these corresponding breaks will not drift as θ is changed. Such a variable which brings this about is t, the momentum transfer squared (or possibly even more appropriate from what we will say below, the variable $\sqrt{-t}$). In Figs. 2(a) and 2(b) we have plotted the same pp, π^+p $(d\sigma/dt)_\theta$ data over again, using the linear $t = -2k^2(1 - \cos\theta)$ variable along the abscissa. It is clear that all the corresponding breaks for different θ line up. To emphasize this point further, we have included in Fig. 2(a) the fixed-angle pp $(d\sigma/dt)_\theta$ for $\theta = 40°$, $30°$, and even $3°$. The $3°$ curve incorporates the recent CERN ISR data[2] at 245, 500, 1070, and 1500 GeV/c equivalent lab momenta, where pp scattering is generally believed to be dominated by optical diffraction.

WHERE ARE THE BREAKS?

For π^+p, the dip or break structures observed so far seem to be located rather clearly at the following positions:

π^+p: $t \approx -0.6$, -2.8, and -5 (GeV/c)^2.

For pp, the breaks seem to us to be located at or near

pp: $t \approx -0.9$, -3, -5.5, -7.5, and -10.5 (GeV/c)^2

as indicated by the curves drawn in Fig. 2(a).

The fact that the various $(d\sigma/dt)_\theta$ curves line up with their breaks at these particular values of t, *whatever the angle* θ, leads to a rather simple interpretation of these breaks and to an important statement about what is happening at large (and small) angles.

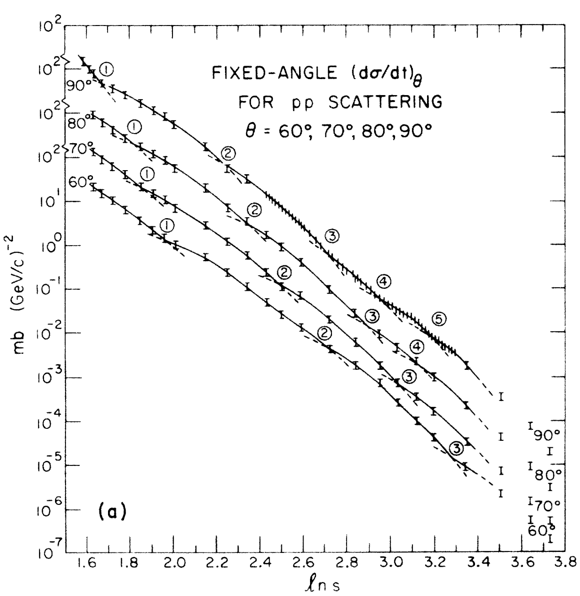
PREVIOUS OBSERVATIONS

The π^+p dips in $(d\sigma/dt)_\theta$ are of course just reflections of the well-known structures[5] in $(d\sigma/dt)_s$. The breaks in pp $(d\sigma/dt)_\theta$, however, indicate subtleties in $(d\sigma/dt)_s$ which are less obvious[6] to the eye. Actually some of these breaks in pp $(d\sigma/dt)_\theta$ have been known for some time. A break around $t \approx -6$ (GeV/c)^2, or equivalently at $\beta^2 p_\perp^2 \approx 2.6$ (GeV/c)^2, was first noticed by Akerlof *et al.* (see Fig. 5 of Benary *et al.*, Ref. 2) and by Krisch,[7] while more recently Kammerud *et al.*[2] suggested the breaks at $t \approx -0.9$ and -3 (GeV/c)^2. At the same time, there have been several theoretical proposals to explain these breaks; we refer the reader to Kammerud *et al.*[2] for a discussion of these.

INTERPRETATION OF THE BREAKS

We wish to suggest that these fixed-angle breaks are due to familiar coherent-scattering phenomena. For the sake of simplicity, we shall interpret these structures in terms of the idealized gray disk model; the conclusions are essentially the same even when a more realistic optical model[8] with smooth impact-parameter profiles is used.

For scattering from a gray disk, the main contribution comes from diffraction, the diffraction amplitude being of the form $D \sim iJ_1(R\sqrt{-t})/R\sqrt{-t}$. If diffraction were important anywhere, that is, present (possibly among other contributions) to a significant degree, one would expect to observe its most noticeable trademark, namely, the oscillations of the J_1 Bessel function. These oscilla-



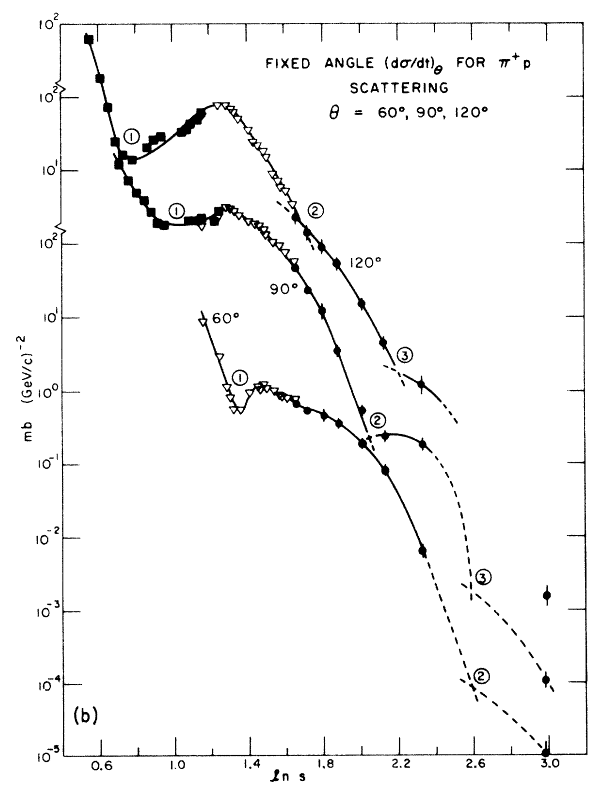


FIG. 1. Fixed-angle differential cross sections for (a) pp, (b) π^+p elastic scattering plotted against ln$s$. Data from Refs. 2 and 3.

tions will be fixed in t, or equivalently in $\sqrt{-t}$. We suggest that, to a large extent, this is what we see in the fixed-angle $(d\sigma/dt)_\theta$.

π^+p BREAKS

For an interaction radius $R = 0.9$ F, the zeros of the J_1 Bessel function occur at $t \approx -0.7$, -2.4, and -5.1 $(\mathrm{GeV}/c)^2$, which indeed are very close to the positions of the breaks observed.

pp BREAKS

The break structure for pp seems to be slightly more complicated than in the π^+p case (probably because the data are much better), and it would seem that a simple diffractive piece alone with $R \approx 0.8$ F which has zeros at $t \approx -0.9$, -3, -6.5, -11 $(\mathrm{GeV}/c)^2$ is not quite sufficient; one needs in addition a peripheral piece, which is typically of the form $iJ_0(R\sqrt{-t}\,)$. [A peripheral piece of this type is of course highly desirable anyway to help explain the crossover in pp, $\bar{p}p$ $(d\sigma/dt)_s$ at $t \approx -0.2$ $(\mathrm{GeV}/c)^2$.] The peripheral piece is almost swamped by the diffractive piece in the forward directions, but for large $|t|$ the two pieces can become comparable and cause a slightly more complicated pattern of oscillations. Our numerical calculations[8,9] bear this out.

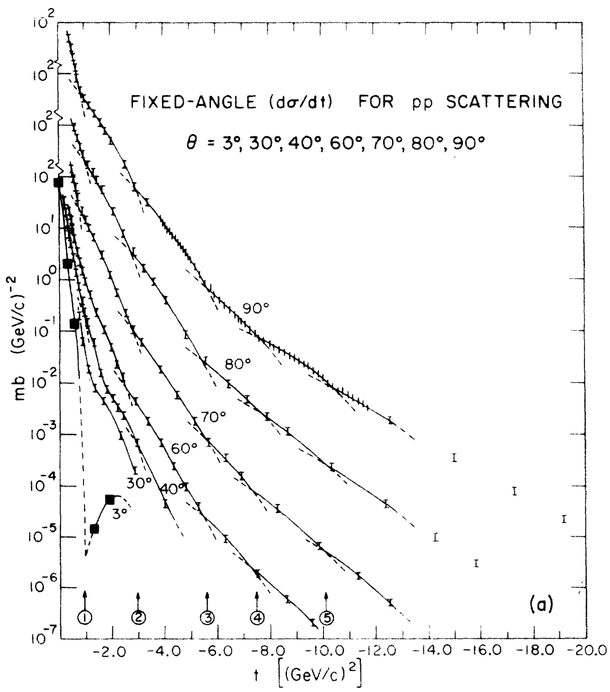
CORROBORATIVE EVIDENCE

In a recent experiment at Argonne, Abshire *et al.*[10] measured the polarization parameter P for pp elastic scattering at 12.33 GeV/c out to very large values of the momentum transfer $|t| \lesssim 6.5$ $(\mathrm{GeV}/c)^2$. This experiment revealed the extremely interesting result that at this energy the pp polarization has a sequence of *double zeros*, at $t \approx -0.8$, -2.4, and -5.5 $(\mathrm{GeV}/c)^2$. This surprising result is very difficult to explain in terms of, say, Regge theories, but is easily interpretable[9] (in fact it was predicted[8]) in terms of a gray-disk type of optical model: Taking the diffraction amplitude with a (peripheral) flip amplitude, one anticipates polarization of the form $[J_1(R\sqrt{-t}\,)]^2/R\sqrt{-t}$. With $R = 0.8$ F, one gets double zeros close to the positions observed, indicating again that the diffractive piece plays a very important role at least out to $|t| \approx 6$ $(\mathrm{GeV}/c)^2$.

CONCLUSIONS

(1) We have examined fixed-angle $(d\sigma/dt)_\theta$ for both π^+p and pp elastic scattering. The evidence for a simple law of the form $d\sigma/dt \sim s^{-n}f(\theta)$ does not seem to be as convincing as has been claimed.

(2) On the other hand, we draw attention to the



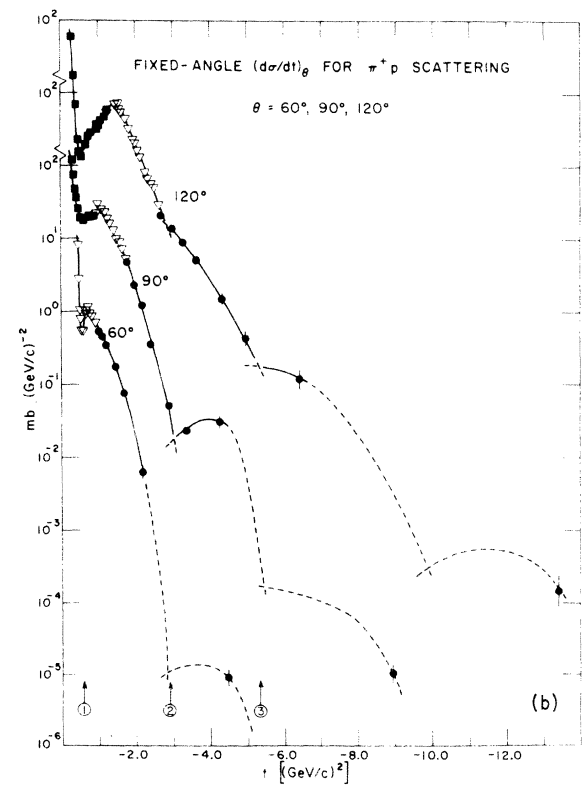


FIG. 2. Fixed-angle differential cross sections for (a) pp, (b) π^+p elastic scattering plotted against t. Data from Refs. 2 and 3.

presence of structure in these fixed-angle differential cross sections, which can all be lined up (whatever the value of θ) when $(d\sigma/dt)_\theta$ is plotted against t.

(3) In the case of pp scattering, these breaks tie in nicely with the double zeros of the elastic polarization.

(4) The above points (1)–(3) follow from an *examination of the data alone,* and do not depend on any model. We note, however, that all the observed structures occur at or near the zeros of Bessel functions, suggesting a substantial diffractive component (and possibly also some peripheral component) even out at large angles ($\theta \sim 90°$). It seems reasonable to conclude therefore that conventional coherent effects, though small (like everything else) at large angles, are certainly not negligible there (as is usually presumed to be the case[1]), and in fact, are present to a rather noticeable degree.

This observation may have important implications for other processes, such as high-energy inclusive processes. For example, a well-known property of inclusive differential cross sections $Ed^3\sigma/dp^3$ is that for larger $p_\perp$ the data get flatter, rather reminiscent of the elastic pp differential cross sections. It will be interesting to see if it is possible also to interpret some of these inclusive data in terms of more standard volume and surface phenomena, which are characterized by a geometric interaction radius rather than by a specific dynamical model.

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[1]For a recent review of parton theories, see S. J. Brodsky, in *High Energy Collisions—1973*, proceedings of the fifth international conference on high energy collisions, Stony Brook, 1973, edited by C. Quigg (A.I.P., New York, 1973).

[2]O. Benary *et al.*, LBL Report No. UCRL-20000, 1970 (unpublished): 1–21 GeV/c; R. C. Kammerud, B. B. Brabson, R. R. Crittenden, R. M. Heinz, H. A. Neal, H. W. Paik, and R. A. Sidwell, Phys. Rev. D 4, 1309 (1971): 1.5–5.5 GeV/c; A. Böhm *et al.*, CERN report, 1973 (unpublished): 250–1500 GeV/c.

[3]C. Lovelace *et al.*, LBL Report No. LBL-63, 1973 (unpublished): 0.5–1.5 GeV/c; K. Abe *et al.*, Maryland Report No. 73-104, 1973 (unpublished): 1.2–2.3 GeV/c; C. T. Coffin, N. Dikmen, L. Ettlinger, D. Meyer, A. Saulys, K. Terwilliger, and D. Williams, Phys. Rev. 159, 1169 (1967): 2.3–4 GeV/c; B. B. Brabson, R. R. Crittenden, R. M. Heinz, R. C. Kammerud, H. A. Neal, H. W. Paik, and R. A. Sidwell, Phys. Rev. Lett. 25, 553 (1970): 3–5 GeV/c; D. Rust *et al.* (unpublished): 3 and 4 GeV/c (agrees with Brabson *et al.*); D. R. Rust, P. N. Kirk, R. A. Lundy, C. E. W. Ward, D. D. Yovanovitch, S. M. Pruss, C. W. Akerlof, K. S. Han, D. I. Meyer, and F. Schmeuser, Phys. Rev. Lett. 24, 1361 (1970): 5 GeV/c; V. Chabaud *et al.*, Phys. Lett. 38B, 441 (1972); and unpublished: 5 and 10 GeV/c; C. W. Akerlof, P. K. Caldwell, P. Kalbaci, D. I. Meyer, K. C. Stanfield, P. N. Kirk, A. Lesnik, D. R. Rust, C. E. W. Ward, and D. D. Yovanovitch, Phys. Rev. Lett. 27, 219 (1971): 5 GeV.

[4]We have also made an exploratory examination of some other processes ($\pi^- p \to \pi^- p$, $\pi^- p$ charge exchange, etc.), not shown here. Though the data are much less plentiful, the corresponding $(d\sigma/dt)_\theta$ possess similar structure.

[5]V. Barger and R. J. N. Phillips, Nucl. Phys. B33, 22 (1971).

[6]The change of slope in pp $(d\sigma/dt)_s$ at $t \approx -1.4$ (GeV/$c)^2$ is well known. Other features, however, such as a point of inflection at $t \approx -3$ (GeV/$c)^2$ for $10 \lesssim p_{\rm lab} \lesssim 20$ GeV/c, are less discernible.

[7]A. Krisch, Phys. Rev. Lett. 19, 1149 (1967).

[8]S.-Y. Chu and A. W. Hendry, Phys. Rev. D 6, 190 (1972); *ibid.* 7, 86 (1973).

[9]A. W. Hendry and G. Abshire, Phys. Rev. D (to be published).

[10]G. Abshire, C. M. Ankenbrandt, R. R. Crittenden, R. M. Heinz, K. Hinotani, H. A. Neal, and D. R. Rust, Phys. Rev. Lett. 32, 1261 (1974).