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Herbert M. Steiner

April 1971

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PION-NUCLEON SCATTERING: Experiments and Phase Shifts

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April 1971

ABSTRACT

A short summary of some recent developments in pion-nucleon scattering experiments and phase shift analyses is presented. Several recent high quality experiments indicate that existing phase shift solutions do not give adequate fits to the data. Some attempts to extend phase shift analyses to higher energies are described.

PION-NUCLEON SCATTERING: EXPERIMENTS AND PHASE SHIFTS

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I. Introduction

The major developments in low-energy pion-nucleon scattering during the last year or so have been (1) more extensive and accurate measurements of cross sections and polarization parameters, and (2) attempts to extend phase shift analyses to higher energies. In this brief status report it is not possible for me to discuss all of the new experimental work nor all of the phase shift analyses. Instead I have somewhat arbitrarily chosen some recent results which serve to illustrate what is happening in this area of research. A more complete summary of results reported prior to September 1970 is contained in Plano's rapporteur's talk at Kiev.[1]

II. Experiments

It is perhaps surprising that experimenters are still spending their time and the taxpayers' money making measurements of pion-nucleon scattering. After all, the pion-nucleon system--because of its relative phenomenological simplicity and experimental accessibility--has been studied much more extensively than any other two-body hadronic interaction. It is hardly necessary to point out that phase shift analyses are based on experimental data and that the "breakthroughs" in our understanding of the πN system--such as, for example, the Saclay[2] and CERN[3] phase shift analyses--were made possible by new and detailed measurements of cross sections and polarizations. Recent experiments have refined and extended these measurements even further,

with the consequence that the existing phase shift solutions no longer give satisfactory fits to the data. To appreciate the significance of some of these measurements let us look at a few examples.

(1) A Cavendish-Rutherford collaboration[4] has recently completed an extensive series of cross-section measurements at the CERN synchrocyclotron, including σ_T for both π^+p and π^-p scattering in the energy range $70 < T_\pi < 290$ MeV; i.e., around the first P_{33} or Δ resonance. The π^+p results are shown in Fig. 1. Note that the accuracy of the points is comparable to the thickness of the line passing through them. An interesting feature of the new data is an apparent shift of the peak of the cross section to a lower momentum. The authors quote the following experimental resonance parameters for the Δ^{++}: mass = 1231.0 ± 0.4 ± 1.4 MeV/c, elastic width = 111.1 ± 0.4 ± 1.8, total width = 111.1 ± 0.4 ± 1.8 MeV/c^2, where the first error is statistical and the second is an estimate of the error arising from uncertainties in the background. Because of the large χ^2 for this fit (χ^2 = 48 for 11 degrees of freedom), the Particle Data Group[5] has tried some other fits--some having much more satisfactory χ^2's--for which $1231 < M < 1234$ MeV/c^2 and $110 < \Gamma < 120$ MeV/c^2, depending on the specific parametrization used. In any case the mass of the Δ^{++} seems to be at least 2 MeV/c^2 lower than had previously been thought. From an analysis of both the π^+p and π^-p cross sections, Carter et al.[4] determined the $\Delta^{++} - \Delta^0$ mass difference to be -2.9 ± 0.9 MeV/c^2, which is in good agreement with the predictions of Socolow[6] of 2.4 MeV/c^2 based on tadpole and baryon-octet self-energy diagrams. In another paper[7] the same group present $\pi^-p \rightarrow \pi^0n$ total charge-exchange cross sections for $90 < T_\pi < 290$ MeV/c. Again the results are of very high quality, having typical errors of 0.3 mb. Very accurate elastic differential cross sections were also obtained during the course of this experiment, and these are expected to be

published soon. The accuracy of these experiments is sufficiently good that more refined consideration of Coulomb effects must be taken into account in the analysis of the data.

(2) The polarized target group at the Rutherford Laboratory has recently completed a painstakingly thorough set of measurements at 68 different momenta of π^+p polarization in the momentum interval $0.68 < p_\pi < 2.5$ GeV/c[8]. An example of the results obtained is shown in Fig. 2. For comparison the results of a 1965 LRL experiment at 1440 MeV/c are shown in Fig. 3. It is perhaps worth keeping in mind that practically all of the present-day phase shift analyses are based predominantly on pre-1966 data. It is also interesting to note that none of the existing phase shift solutions give satisfactory fits to these new data. (See Fig. 4.) We will see more of that later. The general qualitative trends of the data are usually reproduced reasonably well by the phase shift solutions, but the fits are completely unacceptable on a statistical basis.

(3) Recent polarization measurements at CERN[9] and Argonne[10] as well as differential cross-section measurements at CERN[9] are also generally not very well fit by existing phase shift solutions. As an example, some recent cross-section and polarization results are shown in Fig. 5 together with some of the phase shift fits.

(4) In the last year there have been several measurements of backward $\pi^\pm p$ differential cross sections at Saclay[11] and LRL.[12,13] The results are much more accurate and extensive (though in a very limited angular region) than previous measurements. Figure 6 shows the disagreement of some of the new Saclay results with earlier measurements at NIMROD. In Fig. 7 some of the new Saclay data are compared with the phase shift predictions. Some examples of the results obtained by the Iowa State-St. Louis University-McGill collaboration at the LRL Bevatron are shown in Figs. 8 and 9.

Several other very useful and accurate experiments have been reported during the last year, but the above serve as examples of the present state of the experimental information. A summary of existing measurements has been prepared by the polarized target group at the Rutherford Laboratory and is shown in Fig. 10. We note several things: (1) The new measurements extend to higher energies than previously. (2) Accuracy is much better. (3) Spacing of measurements in momentum is in many cases very close. (4) Existing phase shift solutions don't really fit the data well. The new data have been coming in so fast that the phase shifters have as yet not been able to keep up with them. (5) There are still potential unknown systematic errors. In some cases (e.g., total cross section) there exist several "high precision" experiments which give "accurate" but incompatible results. (6) The experimental effort has so far focused almost exclusively on the "easy" experiments (e.g., σ_T and $\frac{d\sigma}{d\Omega}$ for elastic and charge-exchange scattering, and P for elastic scattering).

A word about present developments and plans for the future. At first sight it might appear that the πN system below, say, 2 or 2.5 GeV/c^2 is now well understood in that most of the general features are common to the various phase shift solutions. There is, however, still an urgent need to improve the accuracy of these fits, to reduce the presently large number of acceptable solutions at a given energy, and to find better ways to make the energy continuation of the solutions. To this end the experimental efforts of several groups are being directed toward measurements of heretofore unmeasured quantities such as $P(\pi^- p \rightarrow \pi^0 n)$ (which is presently getting underway at LRL, RHEL, and ANL) and the so-called A and R parameters.

The A and R measurements involve the use of a polarized target and a subsequent analysis of the polarization of the recoil proton. Not only that, but all of the polarization vectors must lie in the plane of the scattering. (See Fig. 11.) Unlike the cross-section and polarization parameters which are proportional to $|G|^2 + |H|^2$ and Im GH^* (where G and H are the non-flip and the flip scattering amplitudes) A and R depend upon ReGH^* and $|G|^2 - |H|^2$. We have performed a rather simple exercise with the

help of a computer which indicates the potential usefulness of some of these A and R measurements. We generated some typical $A(\pi^{\pm}p \rightarrow \pi^{\pm}p)$ and $R(\pi^{\pm}p \rightarrow \pi^{\pm}p)$ data from some of the existing phase shift solutions (see Fig. 12). To do this we distributed a representative number of data points statistically about the phase shift predicted curve. These fake computer-generated A and R data points were then put back into the computer as experimental data along with the real cross-section and polarization data. A new search was then started for sets of acceptable phase shifts which fit all of the input data. The matrix shown in Table I shows what happens to six different "good" solutions at 1080 MeV/c when they have to adjust themselves to fit all of the real data plus the six different sets of A and R results that are generated by each of these solutions. One sees that measurements of a total of 28 points for $A_{\pm}$ and $R_{\pm}$ with an accuracy of ± 0.1 serve to reject all but one or at most two of the original six solutions in each case. Thus it seems likely that A and R measurements of even modest accuracy are likely to be very useful in limiting the number of acceptable solutions at a given energy.

III. Phase Shifts

Although there are lots of groups, lots of methods, and lots of activity it should be made very clear that many of these analyses are not completely independent of each other. They often share common biases such as, for example, the smoothing techniques used in making the energy continuations which bias one against finding resonances, especially narrow ones. Sometimes the choice of "random" starting points used in initiating the minimization procedure to find the phase shifts is not at all random, but instead may be the best solution of a competitor. It may not only be a manifestation of the laws of nature that many different analyses are converging onto a common solution. The question of uniqueness of the existing solutions is not yet definitely settled, although I think most of the "experts" in the field feel that the general behavior of the dominant partial waves is unlikely to undergo major change.

I mentioned before that the phase shifters have not been keeping up with the new data. Instead, the most significant developments have been in extending the solutions to higher energies. For example the Saclay group[14] has recently reported phase shifts up to $p_\pi = 2.8$ GeV/c ($M = 2.5$ GeV/c^2). They cut off their partial-wave expansion at $l_{max} = 5$, which may be just a little low at the higher end of their range, especially since they claim to have found several new resonances such as $H_{1,9}(2200)$ and $H_{3,11}(2320)$ which are $l = 5$ states. These states, if they are confirmed by other analyses, could represent the Regge recurrences of the N(938) and the $\Delta(1234)$. The Saclay analysis fits 3150 data points with 44 parameters. Different variations of the "shortest path" method were used to make the energy continuation. Several other groups have extended their analyses to higher energies. In doing so, various model-dependent assumptions were involved. For example, Bransden and Ogden[15] at Durham have used a model in which the total scattering amplitude can be written as the sum of a Regge amplitude plus another term which can be parametrized as a function of s and t. They used this amplitude as the starting point for a phase shift search. In this way they obtained a solution for $1.95 < p_\pi < 3.5$ GeV/c. Nothing is yet known about the uniqueness of this solution. Bransden and Roychoudhury[16] have recently published a similar analysis in the energy range $1.5 < p_\pi < 2.5$ GeV/c. As one goes to higher and higher energies, especially when the available data are limited in scope, some model-dependent assumptions seem to be unavoidable. Assumptions are all right if they can be checked, but caution should be the watchword when one uses models which can't be tested. Quite a bit of effort has recently gone into making "suitable" models to fit the existing low-energy data. For example, there has been a revival of interest in trying to fit the data with a sum of Breit-Wigner resonances plus a background amplitude which is dominantly the imaginary part of an exponential diffraction-like term.[17]

As we go to higher and higher energies the complexity of standard phase shift method goes up rapidly as the number of parameters increases. To make such analyses tractable one needs ever-increasing computing power.

The present-day analyses have only been possible because of the availability of suitable computers. Clearly, other methods such as, for example, those suggested by Cutkosky,[18] in which the expansion of the scattering amplitude converges more rapidly than in the usual partial-wave decomposition, could significantly facilitate the computer searches.

Many questions remain to be answered. The behavior of the small partial-wave amplitudes is still not well established. The quality of the fits to even the old data is not satisfactory. The old question of how to extract resonance parameters from the phase shifts is still not settled. I think the theorists are falling somewhat behind the experimenters in the efforts they are devoting to this field of research. Hopefully, the availability of the new high-quality experimental data will revitalize not only the activities of the phase shifters but will stimulate the theorists to give renewed attention to the pion-nucleon system.

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Table I. Effect of R and A Data on Phase Shift Analyses.

P_π = 1080 MeV/c. Initially 76 degrees of freedom.
With addition of new data, 100 degrees of freedom.
7 data points per experiment: $A^\pm$, $R^\pm$; $\cos\theta^*$ = .65, .55, .45, .35, .25, .15, .05
($\Delta A^\pm = \Delta R^\pm = \pm 0.1$)

Start Minimizing From Sol'n:

		B2/76	B8/78	C7/97	CH/83	QB/75	YB/90
"Fake"	B2	106/0	156/14	176/13	149/14	560/11	310/15
$A^\pm$, $R^\pm$	B8	128/13	104/0	169/3	120/7	107/2	181/7
Data	C7	120/12	126/3	121/0	139/7	103/5	149/6
From	CH	206/15	157/6	234/6	106/1	144/7	121/2
Sol'n	QB	123/13	109/1	156/2	129/7	101/1	182/6
	YB	223/14	139/8	208/7	120/2	156/8	119/1

Numbers shown are the χ^2 of each fit together with a parameter which indicates how much the solution has shifted from the starting point. This parameter is small (i.e. 0 - 3) if the sol'n is essentially unchanged and large (i.e. > 10) if the solution differs appreciably from the initial one. The underlined numbers indicate "good" solution, i.e. solutions which fit all of the input data satisfactorily.

Figure Captions

Fig. 1. π^+p total cross-section vs pion kinetic energy. The small points are the results of Carter et al.[4] whereas the points with error flags are a representative sampling of earlier measurements.

Fig. 2. Recent π^+p Polarization Results at 1181 and 1441 MeV/c as measured by the RHEL polarized target group.[8]

Fig. 3. Results of a 1965 LRL measurement of polarization in π^+p scattering at 1440 MeV/c.[19]

Fig. 4. Comparison of the new RHEL polarization data at 975 MeV/c[8] with various phase shift fits.

Fig. 5. π^+p polarization and cross-section results obtained at CERN[9] compared with some existing phase shift predictions.

Fig. 6. Recent backward π^-p scattering results from Saclay[11] (dashed curve) and earlier measurements made at NIMROD by Duke et al. (solid curve).[20]

Fig. 7. Comparison of the Saclay backward π^-p scattering data[11] and various phase shift predictions.

Fig. 8. Preliminary results on backward $\pi^-p \rightarrow \pi^-p$ scattering obtained by the Iowa State-St. Louis University-McGill University collaboration.[12]

Fig. 9. Preliminary results of angular distributions near 180° for π^-p elastic scattering obtained by the Iowa State-St. Louis University-McGill University collaboration[12] and some phase shift predictions.

Fig. 10. Summary prepared by the RHEL polarized target group[8] of cross section and polarization measurements in pion nucleon scattering for $0.60 < p_\pi < 2.4$ GeV/c.

Fig. 11. Geometry for A and R measurements.

Fig. 12. Predictions of various phase shift solutions (labelled B8, YB, CH, QB, C7, and C2) for $A(\pi^+p \rightarrow \pi^+p)$ at $p_\pi = 1080$ MeV/c. From the experimental point of view most measurements would have to be made in the portion of the curves labelled "DATA REGION".

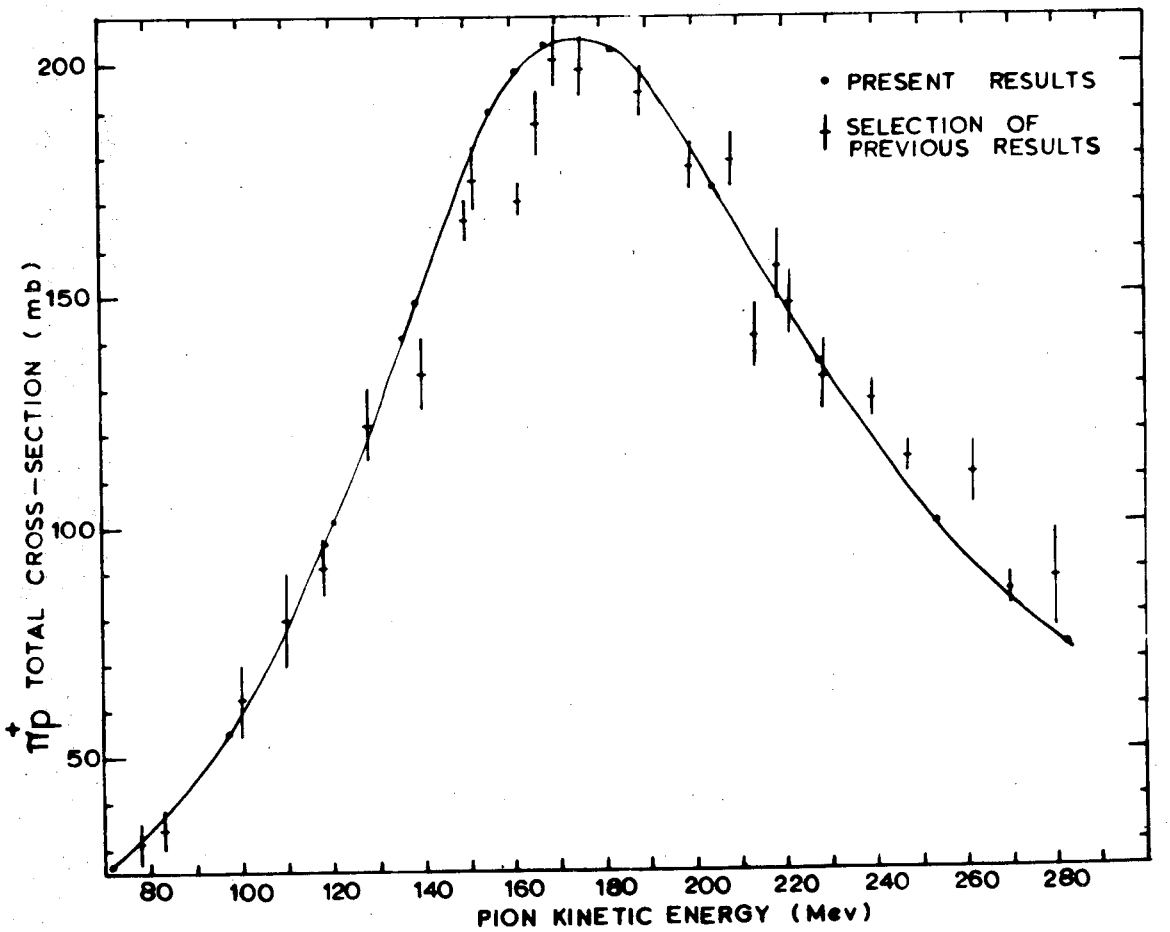

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Fig. 1

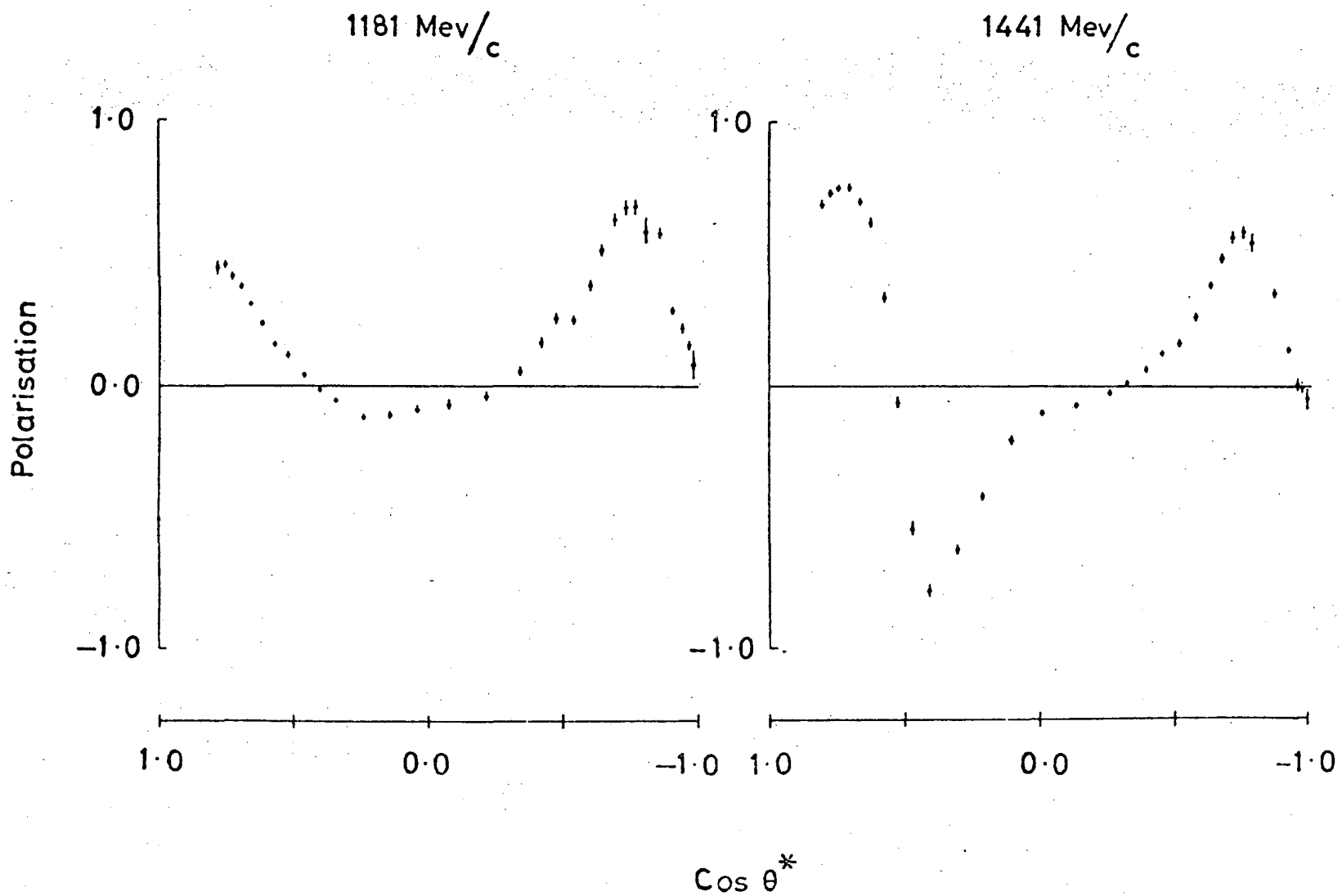

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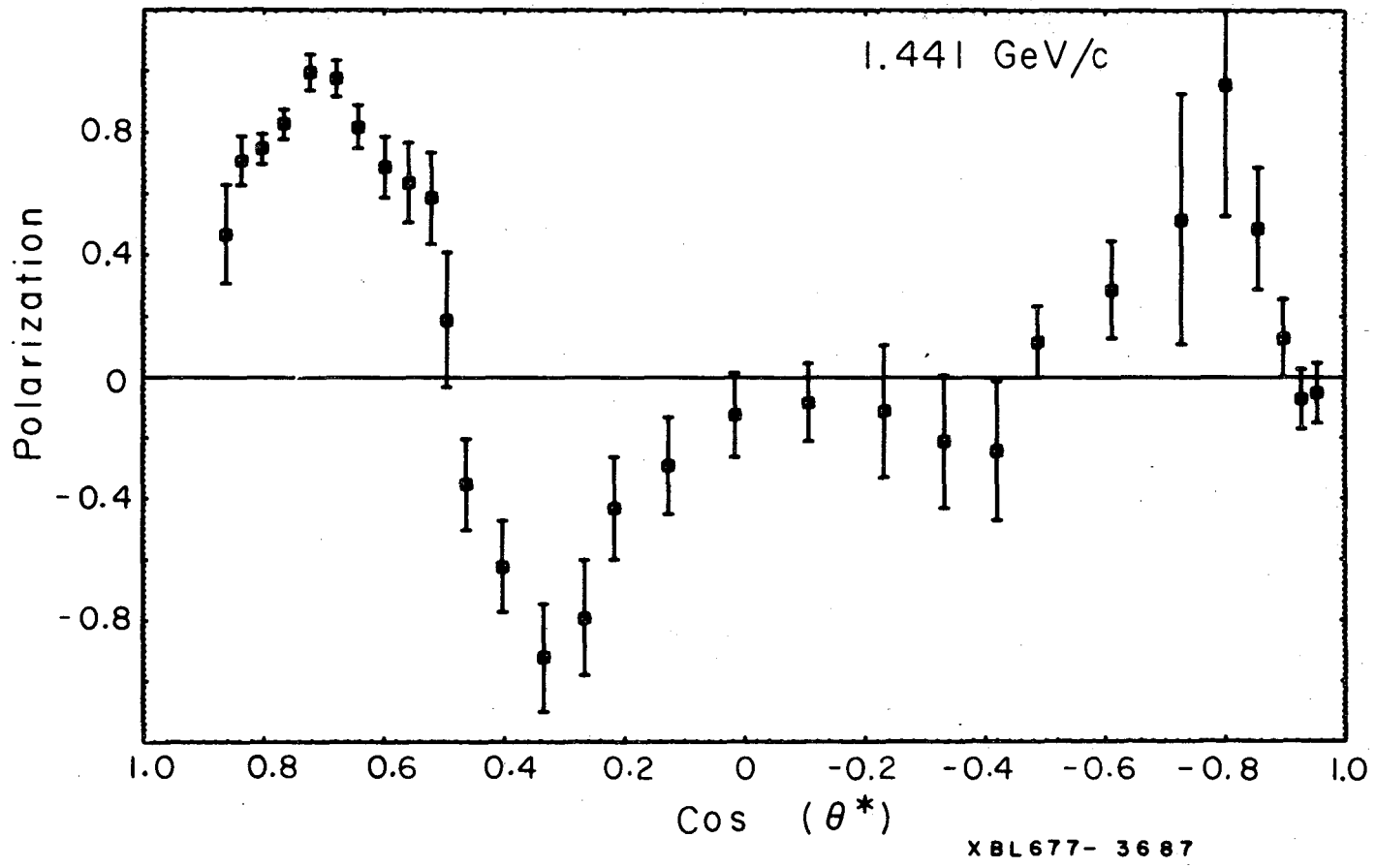
Fig. 2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0.6
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-0.8
1.0
Cos (θ*)
XBL677- 3687

Fig. 3

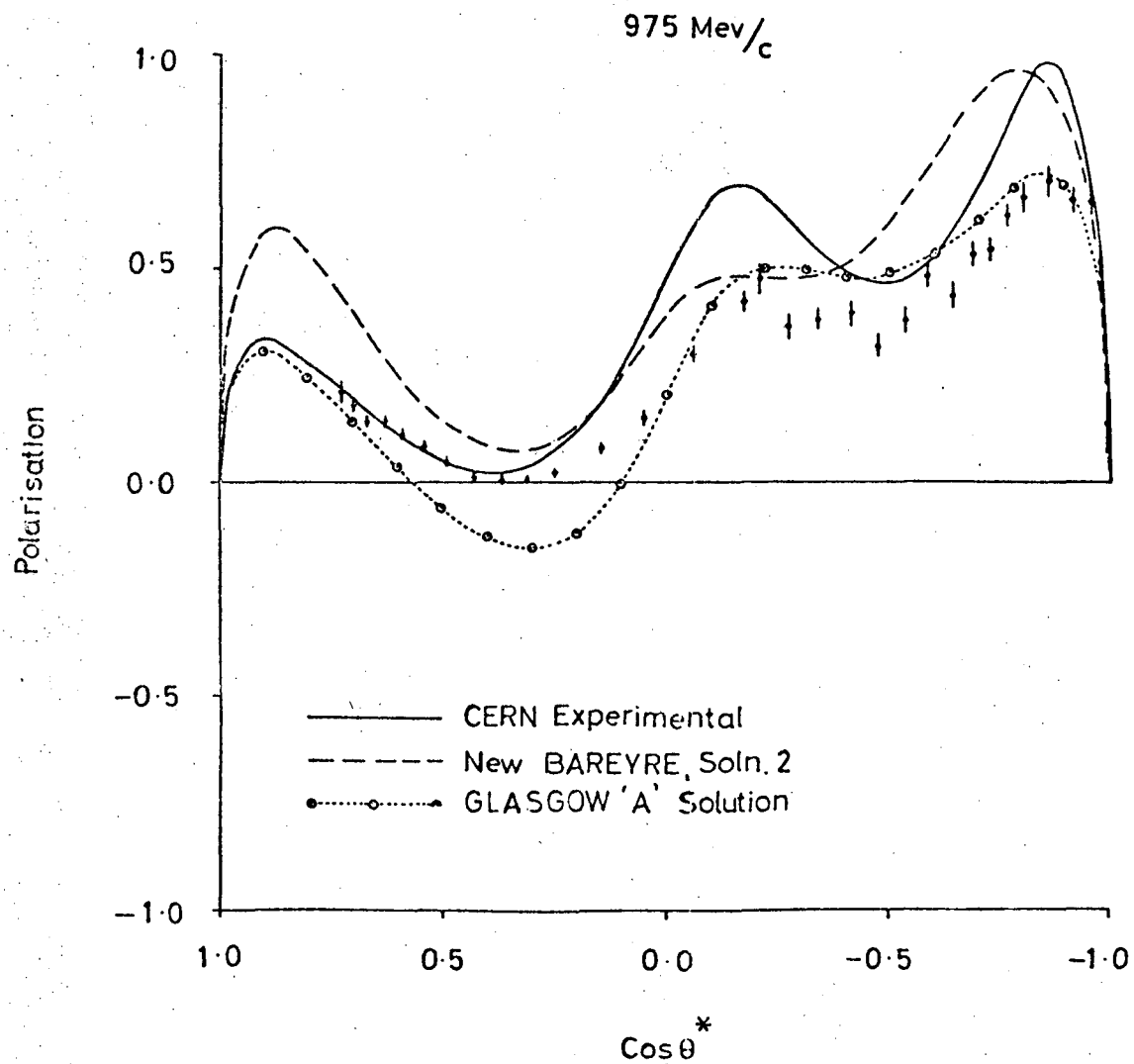

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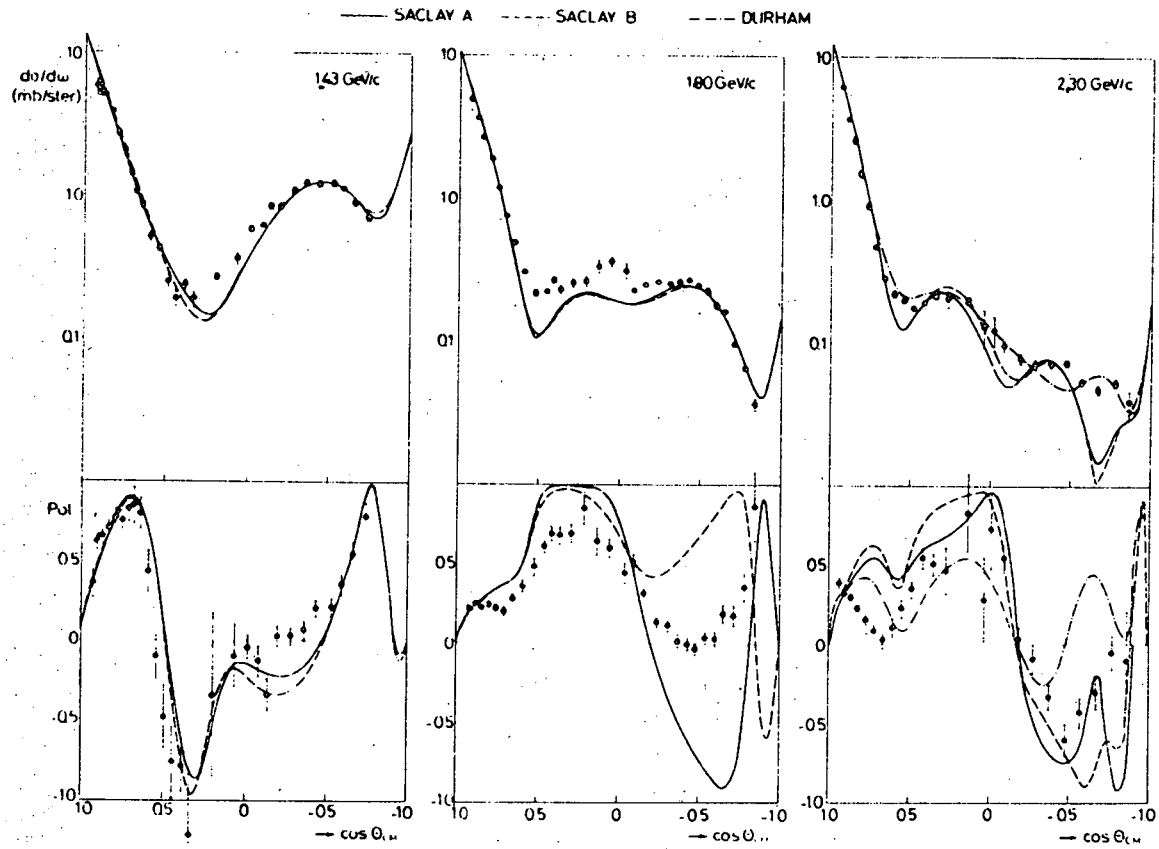
Fig. 4



π^+p ELASTIC SCATTERING
PHASE SHIFT PREDICTIONS (CERN - ALBROW, et al.)

XBL 715-828

Fig. 5

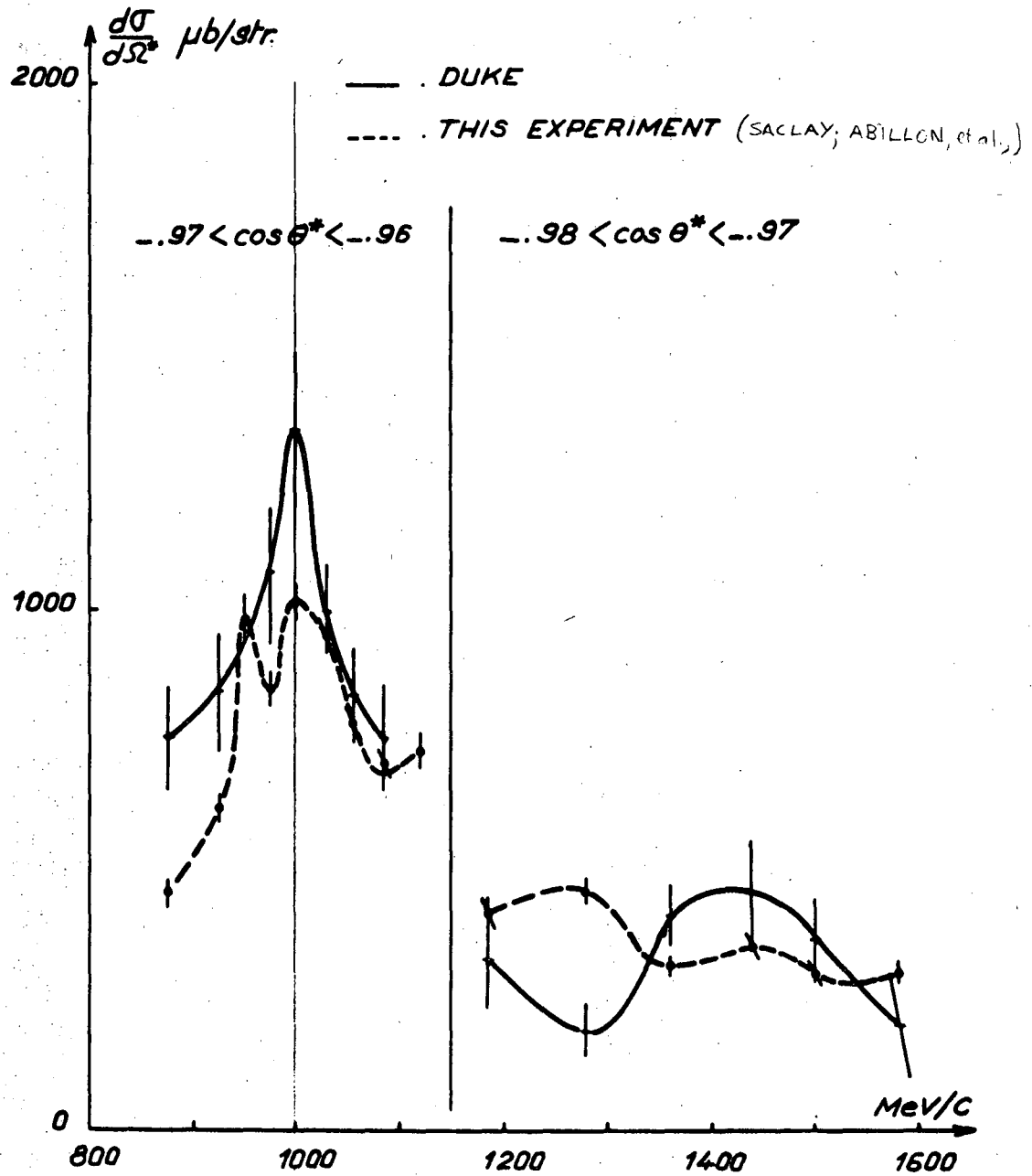


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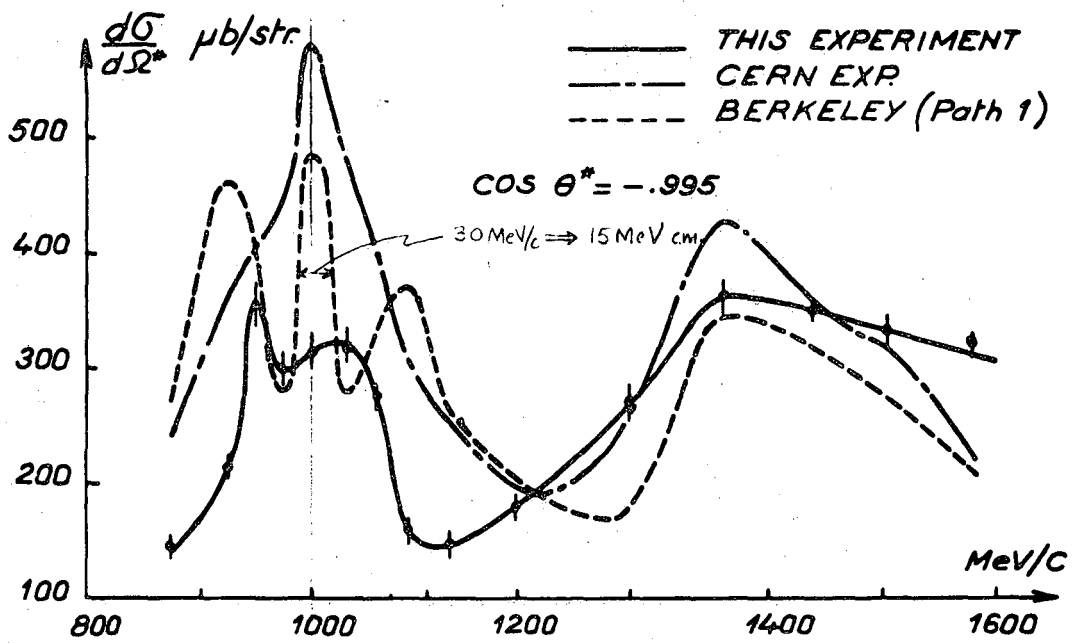
Fig. 6



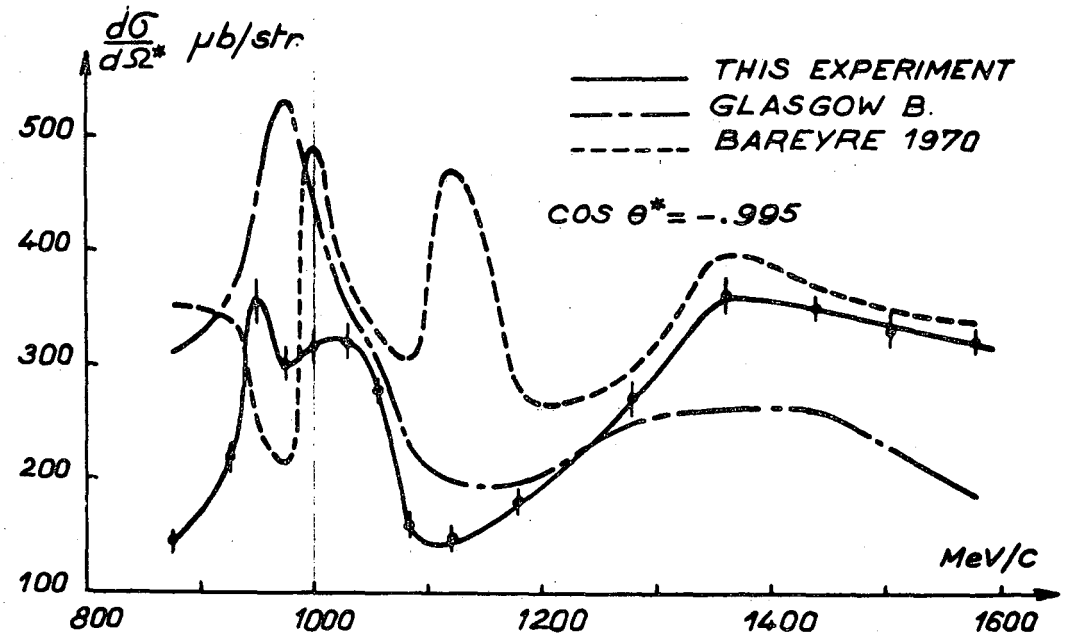


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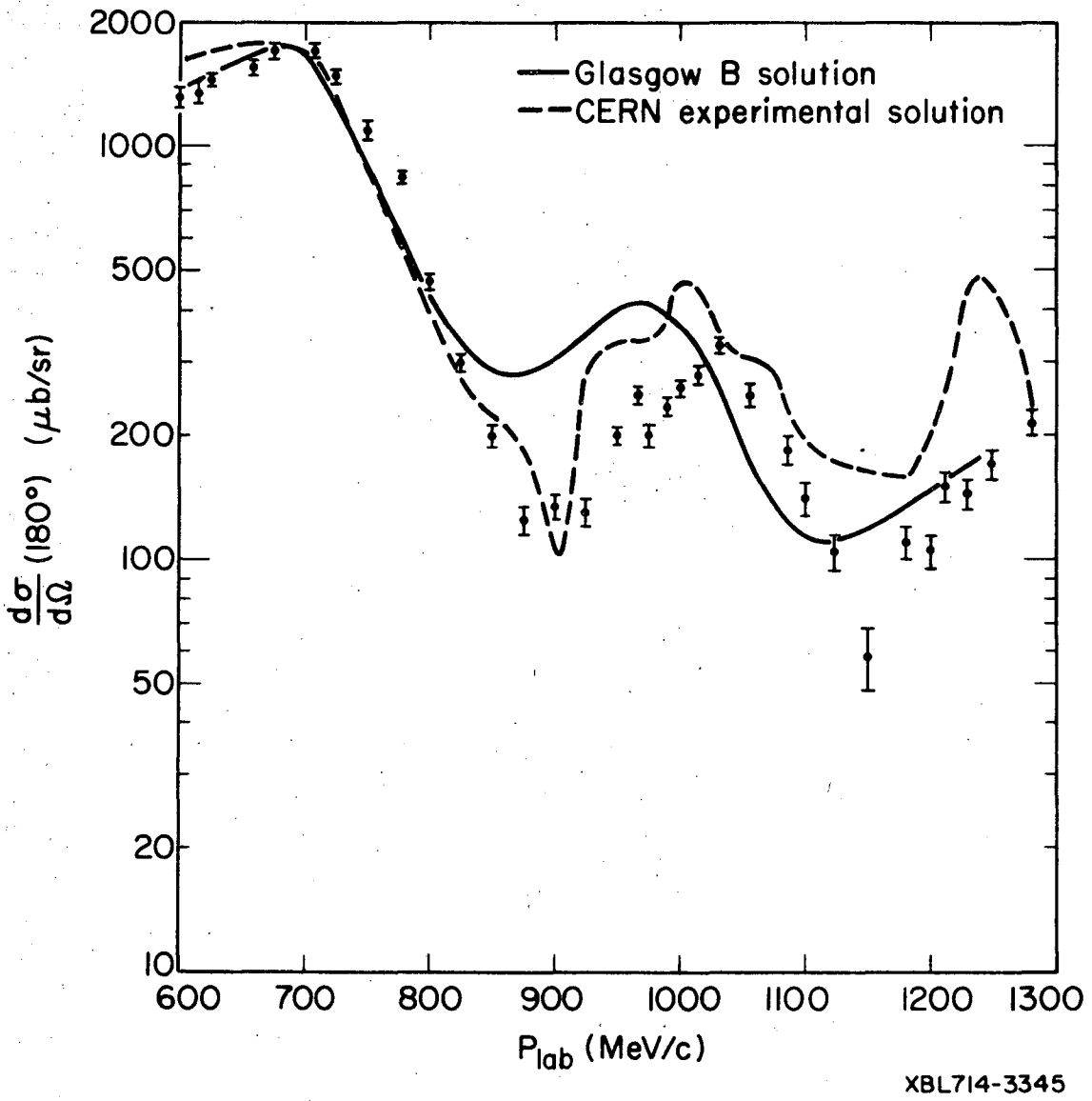
Fig. 7


Glasgow B solution
CERN experimental solution
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1000
500
200
100
50
20
10
600
700
800
900
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1100
1200
1300
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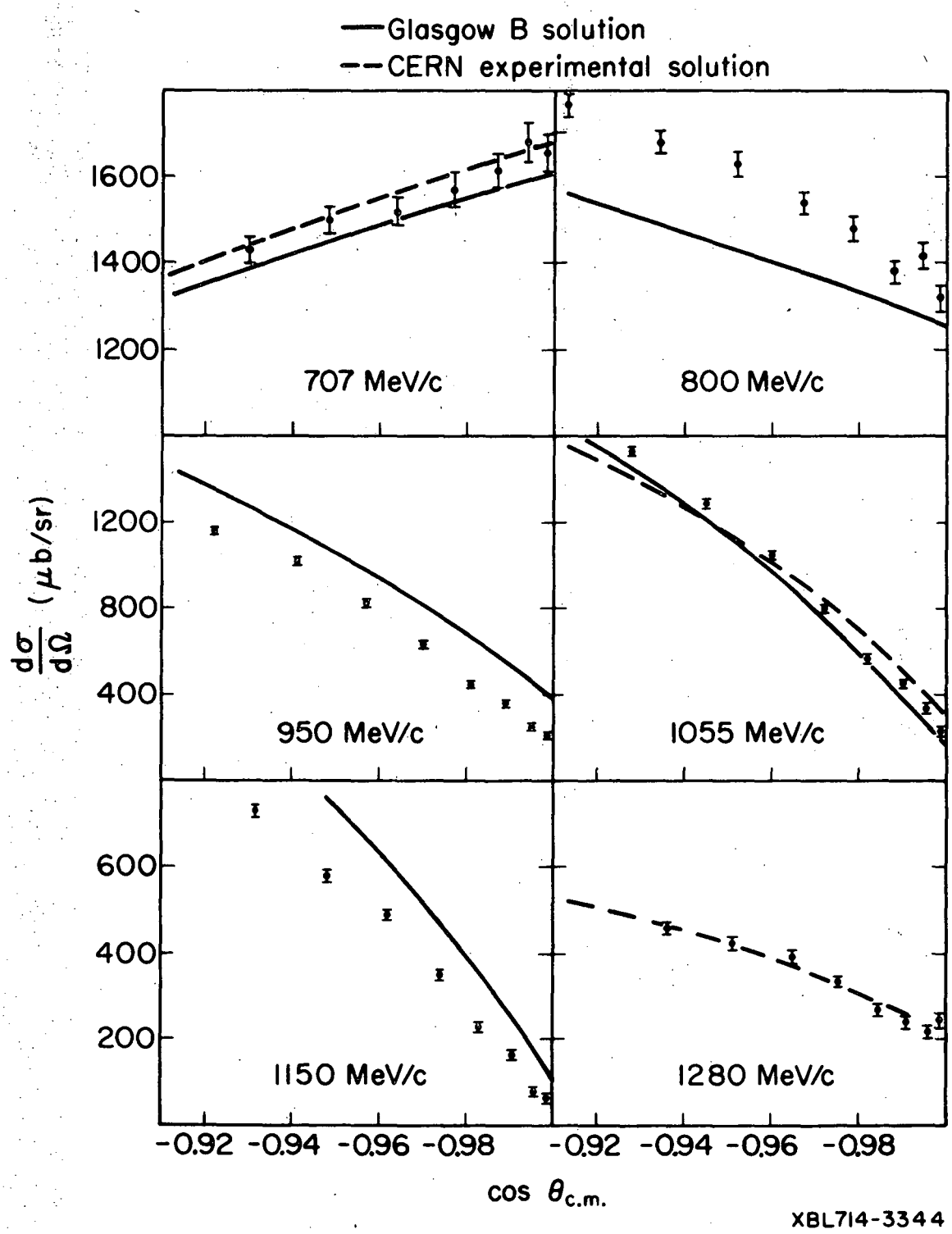
P_{lab} (MeV/c)
XBL714-3345

Fig. 8


Glasgow B solution
CERN experimental solution
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800
400
950 MeV/c
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600
400
200
1150 MeV/c
1280 MeV/c
$\frac{d\sigma}{d\Omega}$ (μb/sr)
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cos $\theta_{c.m.}$
XBL714-3344

Fig. 9

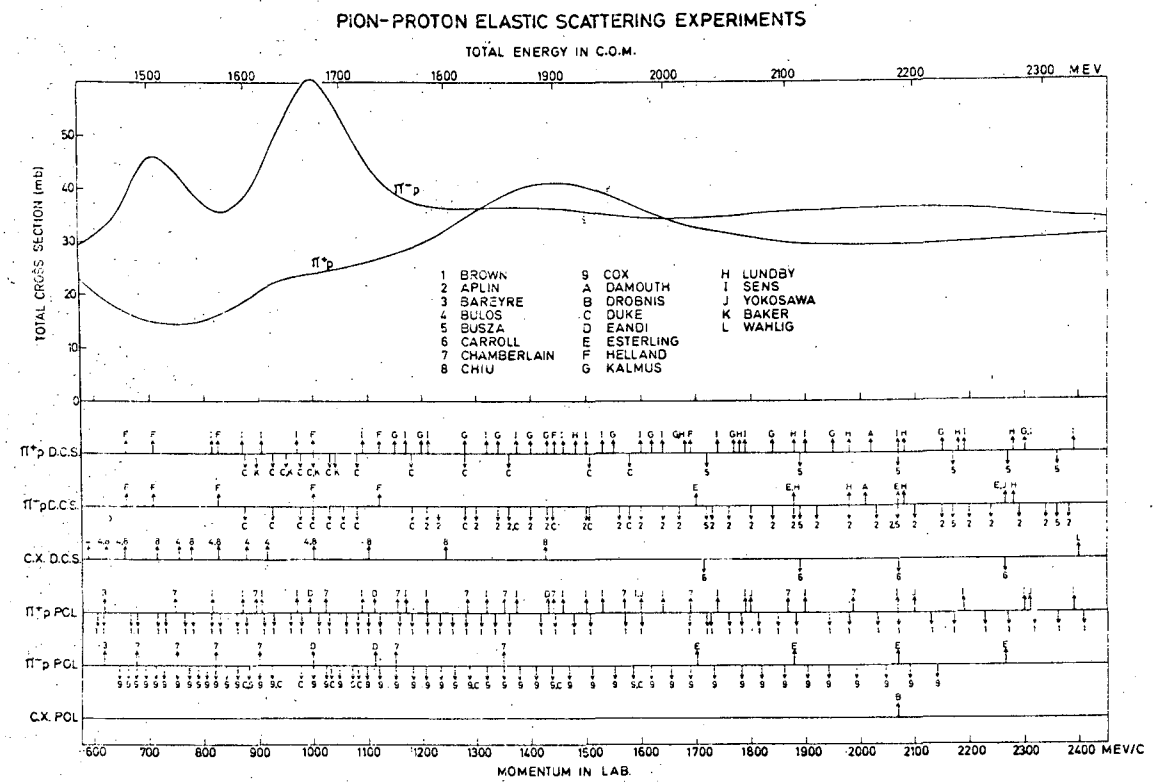

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Fig. 10

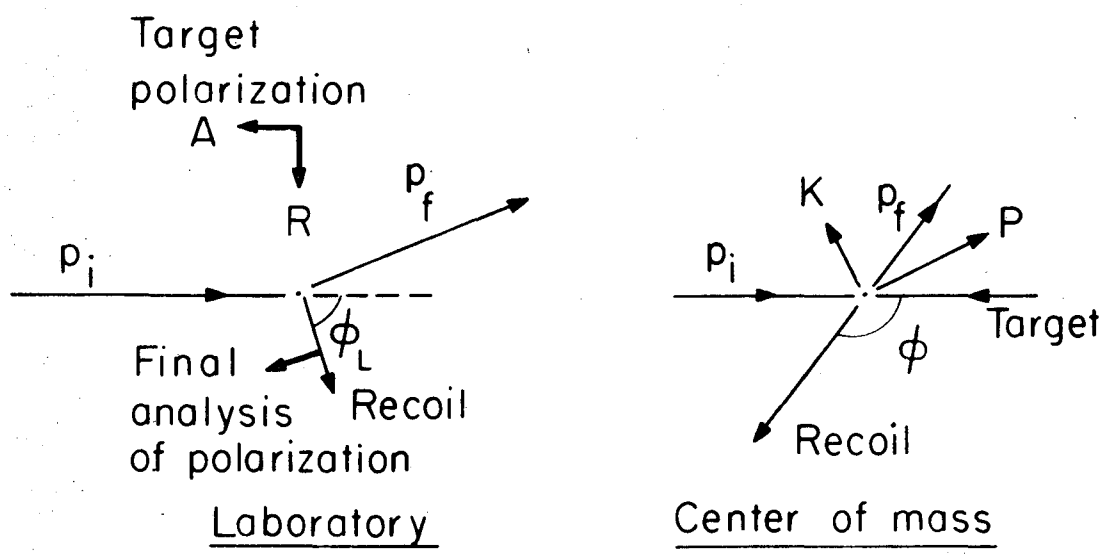

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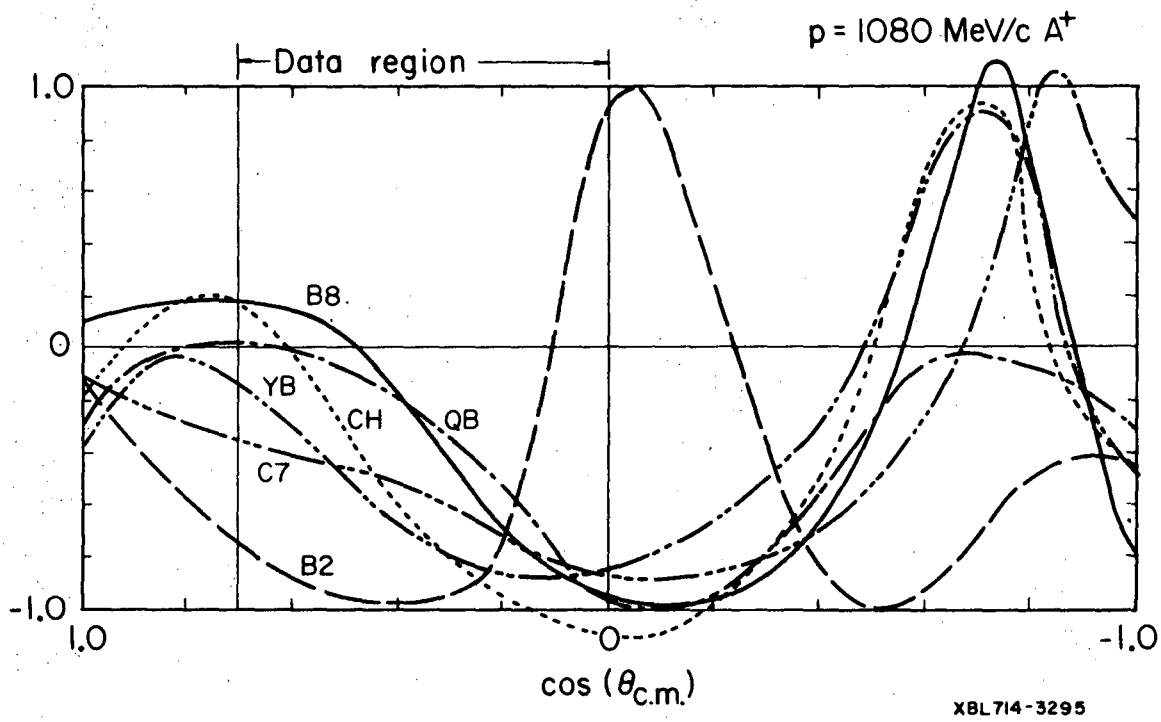
Fig. 11


p = 1080 MeV/c A+
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B8
YB
CH
QB
C7
B2
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0
-1.0
cos (θc.m.)
XBL714-3295

Fig. 12

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