A PROGRAM OF HADRONIC PHYSICS INVESTIGATIONS

By

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The increase in energy provided by the Doubler offers a range of significant new opportunities in hadron physics investigations. In these paragraphs I discuss some of the open questions which may be resolved through studies with the Doubler in its collider mode, and then with external beams. At the risk of being anachronistic, I concentrate on "low- p_T " conventional hadron physics. The hard-core high- p_T specialists have made their case vocally elsewhere at this study, as have the explorers for charm and new phenomena.

1. Doubler-Collider Physics at Small p_T .

1.1 Kinematics

Ignoring the interesting $\bar{p}p$ potential, I assume that the Doubler-Collider will operate with proton beams in both rings. For reference, I adopt values $p_1 = 150$ and 500 GeV/c for the range of the momentum of the protons in beam 1, and I take 10^3 GeV in ring 2. The table below lists the corresponding values of s , $\sqrt{s}$, and $\log s$.

COLLIDER

p_1 (GeV/c)	p_2 (GeV/c)	s (GeV ²)	p_{lab}^{equiv} (GeV/c)	$\sqrt{s}$ (GeV)	$\log s$
150	10^3	6×10^5	3×10^5	775.	13.3
500	10^3	2×10^6	1×10^6	1414.	14.5
<u>(CERN-ISR)</u>					
31	31	3.8×10^3	1.9×10^3	62	8.3

*Paper prepared for the 1976 Fermilab Summer Study

Large p_T processes are known to change on a scale which grows with $\sqrt{s}$, and thresholds associated with new particles and new phenomena are also supposed to be accessible in proportion to the increase of $\sqrt{s}$. However, it is generally conceded that the scaling or nearly-scaling conventional low- p_T phenomena change only on a scale measured by $(\log s)^n$, with $n = 1$ to 3 . This theoretical yardstick may be entirely wrong, but if true it tends to make the increase in $\log s$ provided by the Doubler/Collider look rather modest, only five to six units gain above the top of the ISR range. I believe this conclusion is unnecessarily misleading. As I will describe below, extrapolations of present knowledge show that the increase in $\log s$ provides an important lever arm in energy and, secondly, it opens longitudinal space in the final state significantly. The increase in $\log s$ should be viewed in terms of "correlation lengths" in rapidity.¹ From studies of rapidity correlations, this unit has been determined to be roughly 2. Thus, the collider provides a gain of from 2 to 3 correlation lengths in longitudinal phase space. Since the fragmentation ends of the rapidity distribution each account for 1 or 1.5 of these characteristic lengths, independently of s , we see that the central region of phase space is enlarged from about 2 at the ISR to 5 correlation lengths. This increase should allow clean separation and study of the various hadronic reaction mechanisms¹ which have been identified in studies at Fermilab and at the ISR.

Some of what I include here is a modification of paragraphs I prepared earlier for the POPAE proposal. The results of the first experiments at Fermilab and the CERN ISR quickly changed our ideas about hadronic physics and simple extrapolations to asymptopia. The rise with energy of the proton-proton total cross section, evidence for diffraction minima in the elastic and exclusive inelastic differential cross sections, the relatively large value of the inelastic diffractive cross section, the unexpected copious production of hadrons at high transverse momentum, the opening of a central plateau in the rapidity spectrum of produced pions, and the short-range nature of inclusive correlations have all had important impact. While many important questions have been answered, new ones have been raised.

1.2 Total Cross Sections

At Fermilab and the ISR, the total proton-proton cross section rises, the forward elastic diffraction peaks shrinks, and the real part of the forward elastic amplitude becomes positive.² Will this behavior continue indefinitely, is it rather the threshold onset of the asymptotic domain with properties still unknown, or is it merely a local fluctuation? Theoretical speculations include all of these possibilities. Data are shown in Fig.1. If we regard the present Fermilab/ISR data as suggesting the beginning of an asymptotic domain, the lever arm provided by the Collider is a long probe indeed.

If the growth of the total cross section is parametrized as $\sigma_t = a + b \ln^2 s$, the coefficient b is found to be about

0.5 mb, two orders of magnitude below the Froissart bound. Using this formula, we expect $\sigma_t \sim 80$ mb in the Collider energy range, roughly twice the mean ISR value as shown in Fig.1. A simple logarithmic parametrization also fits the ISR data: $\sigma_t = (25.5 + 2.14 \ln s) \text{mb}$. Extrapolating, we find $\sigma_t = 55$ mb, roughly one and one-half times the ISR value. Other possibilities include a power-like rise ($s^{0.04}$), with the small power being a measure of the distance above unity of the bare Pomeron in the Gribov-Reggeon calculus, or, even a leveling off to some new constant value.

The integrated elastic cross section, σ_{el} , and the integrated inclusive diffractive cross section, σ_{diff} , both of order 8 mb at ISR energies, also grow with energy in the ISR range,³ (Fig.2). Their rate of growth is consistent with being the same as that of σ_t , but the energy range is too narrow to pin down the issue. An important prediction of most models is the energy dependence of the ratios σ_{el}/σ_t and σ_{diff}/σ_t . In a geometrical scaling framework, the ratio σ_{el}/σ_t remains constant, and the common rate of growth of σ_t and σ_{el} measures the rate of growth of the proton's radius.

1.3 Elastic Differential Cross Section

Three kinematic regions of interest may be identified in the study of the elastic differential cross section. At very small $|t|$, one observes Coulomb-nuclear interference effects, from which one may extract the phase of the hadronic amplitude. At somewhat larger $|t|$ values, $0.1 < |t| < 1.0 \text{ GeV}^2$,

effects characteristic of the proton's profile in impact parameter space are studied. At still larger $|t|$ values, one probes hadronic matter at very small distances (≤ 0.2 fermi).

The elastic data presently show a shrinking forward peak.⁴ The logarithmic slope parameter $b = \left[\frac{d}{dt} \ln \frac{d\sigma}{dt} \right]_{t=0}$ increases as $\ln s$ in the ISR range, (Fig.3). Extrapolating to Collider energies, we expect $b \sim 17 \text{ GeV}^{-2}$. An important theoretical issue is whether the logarithmic shrinkage continues, becomes quadratic in $\ln s$ or stops.

A break in the slope of $d\sigma/dt$ near $t = -1.2 \text{ GeV}^2$ in the 10 to 20 GeV energy range develops into a clear diffractive-like dip near $t = -1.4 \text{ GeV}^2$ at Fermilab and ISR energies,⁵ as shown in Fig.4. Insight will be gained from studies of the s dependence of the dip position. In a geometrical scaling model,⁶ the dip moves as σ_t^{-1} and is therefore expected near $|t| = 1 \text{ GeV}^2$ at Collider energies. Beyond the dip, a secondary maximum is observed, and for $|t| > 2 \text{ GeV}^2$, a very shallow slope is measured with $d\sigma/dt \sim 3 \times 10^{-3} \exp(1.81t) (\text{mb/GeV}^2)$ at $\sqrt{s} = 53 \text{ GeV}$. At these large values of $|t|$, the data show no variation with energy in the ISR range.⁵ This plus the shallow slope suggest that the hard scattering limit may already have been reached. If so, the same distribution should be observed at Collider energies. On the other hand, using the geometrical-scaling hypothesis, we expect the large $|t|$ cross section to shrink. At $\sqrt{s} = 2000 \text{ GeV}$, it is predicted to behave as

$$\frac{d\sigma}{dt} = 5.5 \times 10^{-3} \exp [2.5t] \text{ mb/GeV}^2 .$$

Measurements out to $|t| \sim 8 \text{ GeV}^2$ should be well within the range of possibilities at Collider energies. After sufficient shrinkage, will the large $|t|$ cross section reveal a second diffractive dip?

In experiments with external beams, are large $|t|$ dips observed in the πp , Kp , Λp , ... elastic differential cross-sections at high energies? Where or why not?

1.4 Inelastic Diffraction

Important diffractive effects are observed in inelastic processes, in both inclusive and exclusive processes. In the exclusive reaction $pp \rightarrow (n\pi^+)p$ at the ISR, and in $np \rightarrow (p\pi^-)p$ at Fermilab, a dip is observed⁷ in the production differential cross section near $|t| = 0.2 \text{ GeV}^2$. The dip position moves to larger $|t|$ values as the excitation mass increases. While the full meaning of these data is not yet clear, one important deduction is that the elastic and inelastic diffractive processes are very different.^{8,9}

A central question in the further study of diffraction is whether the Pomeron, as a factorizable t -channel singularity, may be exchanged twice. If so, one expects a double-Pomeron amplitude leading to particle production in the central region of rapidity space. At the highest ISR energies, the available rapidity interval is barely large enough to allow kinematic separation of the conjectured double-Pomeron signal from the large background of single diffractive excitation. In doubling the range of available rapidity, the Collider may provide an

unambiguous test of this important concept, while simultaneously allowing the subenergy of the Pomeron-Pomeron system to approach the present overall ISR energy.

The inclusive inelastic process $pp \rightarrow pX$ at small $|t|$ and large $x(>0.90)$ is described theoretically by the triple-Regge formalism. At Collider energies, masses M_X of more than 300 GeV are expected to be excited diffractively. One important deduction from Fermilab and ISR data is that the triple-Pomeron term appears not to vanish as $|t| \rightarrow 0$. The validity of this conclusion could be subject to a very stringent test at Collider energies, and the detailed dependence of the triple Regge amplitudes on M_X will be established.

1.5 Multiparticle Production

The nondiffractive production of particles at small transverse momentum accounts for the bulk of the inelastic cross section ($\sim 2/3$). Changes in the character of this dominant mechanism may be substantial over an energy range in which the total cross section could double.

In proton-proton collisions with $\sqrt{s} > 10$ GeV, the rate of growth of the mean multiplicity of charged hadrons may be parametrized¹⁰ as $\langle n_{ch} \rangle \sim -3.19 + 1.84 \ln s$. At $\sqrt{s} = 1000$ GeV, this expression suggests an average of 22 charged hadrons per inelastic collision. Higher values are predicted by parametrizations including terms such as $(\ln s)^2$ or s^n , as shown in Fig.6.

As predicted by models based on short-range-order concepts, and supported by data from Fermilab and the ISR, it is generally believed that the inclusive yield of these hadrons will be

characterized by a plateau in rapidity space. Multiperipheral and other models, such as the Mueller-Regge approach, which are dominated by short-range order, require that the magnitude of the inclusive correlations between hadrons should decrease rapidly as the rapidity spacing between the hadrons is increased. While this expectation is consistent with the ISR data, other requirements of pure short-range order models fail seriously. The height $h(s)$ of the rapidity plateau is predicted to reach a constant limit as energy increases, whereas the ISR data¹¹ in Fig. 7 show a rate of increase of the plateau height for pions as much as two or three times that of σ_t . Pure short-range order is also ruled out by the observed growth of σ_t itself. As of yet, no self-consistent hadron theory explains the rise of σ_t and the behavior of the inclusive spectra. Promising models exist, based on the Reggeon calculus,¹² for example. Long-range correlations are expected to play a significant role in our eventual understanding. Isolating the long from the short-range components of the correlations in various experimental distributions is now impossible even at the highest ISR energy because the phase space is too restricted. The full rapidity interval provided by the Collider may make it possible both to isolate and to study the properties of long-range inclusive correlations. For further discussion of correlations, consult the article "Some Issues in Hadron Physics" elsewhere in these proceedings.

2. External Beams

The doubler both extends the momentum range and provides an important increase in the intensity of external secondary beams. In this section I discuss a few interesting external beam experiments, again, always in the small- p_T domain. I divide the remarks into two categories. first, reactions for which the cross-section is presumed to be roughly energy independent ("Pomeron physics"), and in Sec.3 exchange processes having cross-sections which decrease as a power of the incident momentum. Obviously some of the remarks made in Sec.1 for pp collisions apply also for external secondary beam physics. The list is hardly exhaustive.

2.1 Total and Elastic Cross-Sections

Section 1.1 applies for all beams: $\pi^\pm$, $K^\pm$, $\bar{p}$, $\bar{\Lambda}$, charm,... The K^+p results at high energy are interesting in that the "asymptotic" rise with energy appears to set in at a lower energy for K^+p (~ 30 GeV/c) than for protons (~ 70 GeV/c). If the present rise with energy of the total cross-sections should be a transient threshold phenomenon, perhaps a new flat behavior will appear first in the K^+p results.

Does the $\bar{p}p$ total cross-section always stay above the pp value?

What is the energy dependence of the $\pi^+\pi^-$ total cross-section? Does its asymptotic rise begin as low as the first prominent inelastic threshold (~ 1 GeV/c)?

The structure observed at various $|t|$ values in elastic differential cross-sections is not understood. Experiments with

different beams will allow us at least to sort out the s and t channel quantum numbers of the structure, and its s dependence. Because there are fewer spin amplitudes in meson-baryon scattering (and fewer quarks in the beam) meson-baryon processes may be easier to understand.

2.2 Inclusive Processes

In "Some Issues in Hadron Physics" elsewhere in these proceedings, I comment on the importance of two particle inclusive correlations. I will not repeat those remarks here.

Triple-Regge processes such as $h_1 p \rightarrow h_2 X$ have a phenomenology of their own and will especially benefit from an increase of the incident energy.¹³ The applicability of the model is restricted to large M_X^2 and large s/M_X^2 . Requiring $M_X^2 > 10 \text{ GeV}^2$ and $s/M_X^2 > 10$, we see that s must be $> 100 \text{ GeV}^2$, or $p_{\text{lab}} > 50 \text{ GeV}/c$. It will be interesting to sort out the different triple-Regge terms¹³ once a good set of data is available. Valuable processes include $\pi^\pm p \rightarrow \pi^\pm X$, $K^\pm p \rightarrow K^\pm X$, $\pi^\mp p \rightarrow \pi^0 X$, as well as the too-often forgotten inclusive resonance production processes, e.g. $hp \rightarrow (\rho, \phi, \eta, \eta')X$. The impact of the larger than expected measured values of the inclusive e^-/π^- , and μ^-/π^- ratios as a function of p_T would certainly be more evident if we had a more complete set of data on the vector meson and of the η and η' inclusive yields as a function of p_T . Some of the "new physics" may not be so novel.

2.3 Is the Pomeron a t-channel exchange?

The elastic scattering amplitude can be parametrized as if it were. Its contribution to the elastic amplitude is roughly exponential and factorization seems to be satisfied near $t=0$. However, in exclusive inelastic processes, such as $np \rightarrow (p\pi^-)p$ and $pp \rightarrow (n\pi^+)p$, a marked dip is observed near $|t| = 0.2 \text{ (GeV/c)}^2$ in $d^2\sigma/dt dM^2$ for values of M near threshold.⁷ The Pomeron's t dependence is therefore very different in elastic and in inelastic processes (central versus peripheral when restated in impact parameter language^{8,9}). Further progress in understanding this difference might come from good measurements of the polarization in $pp \rightarrow (n\pi^+)p$. I have in mind the kinematic configuration in which a polarized target is used and the $(n\pi^+)$ is fast in the laboratory (beam dissociation). Data on proton target dissociation from a polarized proton target would be useful for establishing the spins and parities of the N^* resonances which are apparently produced diffractively.⁷

Recently a SLAC group¹⁴ completed a very high statistics experiment on $K^\pm p \rightarrow (K^\pm \pi^+ \pi^-)p$. They identify one and perhaps two resonances near 1.3 GeV in the $(K^\pm \pi^+ \pi^-)$ system, which appear to be produced diffractively. A similar analysis should be carried out at much high energy, e.g. 200 GeV/c. Does the $K\rho(K^*\pi)$ subsystem continue to be produced with $s(t)$ channel helicity conservation at much increased incident momentum?

Assuming that the Pomeron is a t-channel exchange and not some purely direct-channel shadow effect, we can draw diagrams

in which it is exchanged twice, as in Fig.5(a). In the double Pomeron process sketched in Fig.5(a), the central vertex may represent an inclusive configuration (anything, summed over) or an exclusive state such as $\pi^+\pi^-$ or K^+K^- with $I=0$. It will be of great value theoretically¹⁵ to establish whether a double Pomeron signal is present, and the nature of the distributions in t associated with the Pomeron exchanges. A practical advantage of external beams is that the momentum transfers can be more readily restricted to be very small.

2.4 Does the Pomeron Flip Spin?

Data from Serpukhov on the energy dependence of $\pi p \rightarrow A_2 p$ suggest that it does.¹⁶ These measurements should be extended to much higher energies. Does the Pomeron contribute in a spin-flip mode also to $K^\pm p \rightarrow K^*_{890} p$?

If there is a spin-flip coupling of the Pomeron to the nucleons in $\pi^\pm p \rightarrow \pi^\pm p$, we may expect interesting polarization effects at high energy ($p_{lab} \gtrsim 100$ GeV/c). At low energy, the famous and well understood mirror symmetry rule holds whereby $P(\pi^+ p) = -P(\pi^- p)$, and $P \propto 1/\sqrt{s}$. If a Pomeron-Pomeron interference term dominates the polarization at high energy, we should find an energy independent polarization parameter, with $P(\pi^+ p) = +P(\pi^- p)$.

3. Exchange Processes and Spectroscopy .

Many reactions of substantial dynamical interest have cross-sections which are expected to fall as an inverse power of laboratory momentum. Existing data on these processes from ANL, BNL and the CERN PS are usually limited to lab momenta $\lesssim 20$ GeV/c, although some higher energy results are available from Serpukhov.

The range of momentum values of relevance at Fermilab is from 10 to roughly 200 GeV/c.

A few showcase charge-exchange processes are listed below, along with their t channel Regge exchanges.

	Reactions	Exchanges
1.	$\pi^- p \rightarrow \pi^0 n$	ρ
2.	$\pi^- p \rightarrow \eta n$	A_2
3.	$K^- p \rightarrow \bar{K}^0 n$	$\rho - A_2$
4.	$K^+ n \rightarrow K^0 p$	$\rho + A_2$

Data from the Caltech Fermilab experiment¹⁷ on $\pi^- p \rightarrow \pi^0 n$ suggest that simple Regge pole exchange model ideas are valid to an impressive degree throughout the Fermilab energy range. It would be useful to complement these data with a detailed study of the reactions 3 and 4, above. These are related by line-reversal in the t -channel and should have identical differential cross-sections if duality/exchange-degeneracy ideas are valid.

The hypercharge exchange processes

$$5. \quad \pi p \rightarrow K\Lambda$$

$$6. \quad \bar{K}p \rightarrow \pi\Lambda$$

are mediated by (K^*, K^{**}) exchange. A diligent investigation of these processes, including a polarized target and determination of Λ polarization would yield directly the two complex spin amplitudes.¹⁸

Regge exchange phenomenology appears inconclusive to many, but sight should not be lost of its many qualitative successes.¹⁹

It is defensible to attribute at least some of its apparent failures to over-exploitation in an age in which data were not available in the appropriately high range of energies. With $p_{lab} \gtrsim 20$ GeV/c in the Meson Area at Fermilab, the model may finally be tested properly.

Conventional spectroscopy may yield many rewards (even when viewed as a mere by product of the search for charmed hadrons). The discovery²⁰ of the h meson at Serpukhov was a triumph of painstaking investigation. It presumably has spin-parity $J^P = 4^+$, and lies on the $(\rho, f, g, h, \dots)$ Regge trajectory. Nothing is known experimentally about its strange (and otherwise) partners in the 4^+ SU(3) nonet. The g meson ($J^P = 3^-$) is also a relatively lonely member of an as yet incomplete multiplet. I will refrain from mentioning the sordid state of the $J^P = 1^{++}$ and 1^{+-} multiplets. Neutral decay modes often go undetected for technical reasons. Narrow high mass states with primarily electromagnetic decays modes ($\rightarrow \gamma, \rightarrow e^+e^-, \dots$) may await discovery. These states are of interest in their own right and may explain the large values of the inclusive e^-/π^- , μ^-/π^- , and γ/π ratios as a function of p_T .

Finally, double-peripheral processes deserve some emphasis. A typical example is sketched in Fig.5(c). The diagram contributes to the region of phase space defined by small $t_{\pi\pi^0}$ and t_{pp} , but large $m_{\pi\pi^0}^2$, $m_{\pi p}^2$, and s . Relatively large incident energy is required to satisfy these criteria. The data are important for a precise verification that exchange ideas

can be extended beyond $2+2$ processes. They will give us a valuable measure of the nature of the two-Reggeon single-particle vertex, which is a building block in many a theoretical edifice.

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FIGURE CAPTIONS

1. Data on the pp total cross section and two representative phenomenological extrapolations into the Collider energy range.
2. Inclusive diffractive cross-section σ_{diff} defined as the integral for $x \geq 0.9$ of the proton inclusive yield from $pp \rightarrow pX$. ISR data (Ref.3) are shown with two sample extrapolations.
3. Energy dependence of the logarithmic slope of the forward elastic pp differential cross-section.
4. Data from the CHOV-ISR collaboration (Ref.5) on the large $|t|$ behavior of the pp elastic differential cross-section.
5. (a) Double-Pomeron exchange diagram.
(b) A triple-Regge process; h_1 and h_2 are hadrons.
(c) Double-peripheral exchange diagram for $\pi^-p \rightarrow \pi^0\pi^-p$.
6. The average multiplicity of charged hadrons as a function of energy, along with two possible extrapolations, from Ref. 10.
7. The height of the inclusive plateau for π^- production in the central region of rapidity space ($y_{\text{cm}} = 0$). The straight line is $-2.73 + 6.4 \log \sqrt{s}$. From Ref. 11.

Fig. 1

Fig. 2

Fig. 3

Fig. 4

(a)

(b)

(c)

Fig. 5

Fig. 6

Fig. 7