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A Proposal to Measure Cross Sections for $pp \to pX$, nX as a Function of s and M_x^2 Using the Internal Target Facility at NAL

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NATIONAL ACCELERATOR LABORATORY

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Abstract

A simple counter experiment is proposed to investigate the s and s/M^2 dependence of the invariant cross section for the single particle inclusive reactions $pp \to pX$ and $pp \to nX$ in a limited region of phase space

$$4 < s/M^2 < 20, \quad 40 < s < s_{max}, \quad 0.1 < |t| < 0.6$$

near the kinematic limit. The neutron reaction will be studied directly, using a hydrogen jet, and also by measuring the difference between $pp \to pX$ and $pD \to pX$ using a deuterium jet. The latter will provide information on the line reversed reaction $pn \to pX$.

The proposed experiment will use the internal target and aims to provide information on specific theoretical issues in a very short time interval. These issues are:

1) Relative importance of PPP and PPR couplings in the triple Regge framework.

2) Diffractive versus triple Regge approaches to the understanding of single particle inclusive reactions.

Physics Justification

Theoretical progress since 1970 has revealed the physics interest of single particle inclusive distributions . As a result of this progress it is now possible to do simple experiments in this field, covering a very small region of phase space and designed to be relevant to specific theoretical issues[1].

This is the spirit of our proposal and in this context we aim to answer experimentally a limited number of questions in a very short time interval. The questions are the following: Can the triple Regge graph provide a reasonable description of $pp \rightarrow pX$ and $pp \rightarrow nX$ at NAL energies? If this is the case what are the relative magnitudes of the triple Regge couplings? How do they compare with values obtained from other experiments (in particular ISR)?

A different approach to the understanding of single particle spectra at high energy is that of the "Diffractive" type models (Fireball, Nova, Diffrative Excitation etc.)[2]. Triple Regge and Diffractive models can fit equally well the ISR data on $pp \rightarrow pX$[3]. However, as we shall show below, the two approaches lead to very different predictions for the magnitude of $pp \rightarrow nX$ as compared to $pp \rightarrow pX$. By studying the two reactions simultaneously we will be able to differentiate between the two types of models.

The Triple Regge Approach

In the limit $s \to \infty$, $M^2 \to \infty$, $s/M^2 \to \infty$ the invariant cross for $a + b \to c + X$ is given by[4]:

$$\frac{s\,d^2\sigma}{dt\,dM^2} \propto \frac{1}{s} \sum_{ijk} G(t)_{ijk} \, (s/M^2)^{\alpha_i(t) + \alpha_j(t)} \, (M^2)^{\alpha_k(0)} \qquad (1)$$

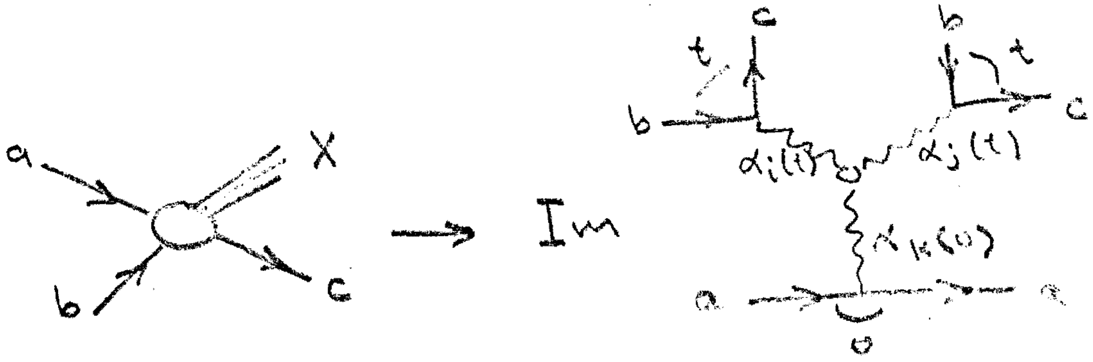


Fig. 1

where $s = s_{ab} = (p_a + p_b)^2$

$t = s_{b\bar{c}} = (p_b - p_c)^2$

$M^2 = s_{ab\bar{c}} = (p_a + p_b - p_c)^2$

$G_{ijk}(t) = \beta(t)_{ibc}\, \beta(t)_{jbc}\, \beta(0)_{kaa}\, g(t)_{ijk}$

The assumption is usually made that cross terms of the form $i \neq j$ do not contribute to (1). Table 1 gives the functional dependence on s (for s/M^2 fixed) and on s/M^2 for s fixed) of the possible contributions to expansion (1). We have restricted the list to terms falling at most like $s^{-\frac{1}{2}}$.

Table 1

ijk	s/M^2	s	We assume
PPP	$(s/M^2)^{1+t}$	constant	$\alpha_P(t) = 1 + \frac{1}{2}t$
PPR	$(s/M^2)^{3/2+t}$	$s^{-\frac{1}{2}}$	$\alpha_R(t) = \frac{1}{2} + t$
RRP	$(s/M^2)^{2t}$	constant	$\alpha_\pi(t) = t$
RRR	$(s/M^2)^{1/2+2t}$	$s^{-\frac{1}{2}}$	
$\pi\pi$P	$(s/M^2)^{2t-1}$	constant	
$\pi\pi$R	$(s/M^2)^{2t-1/2}$	$s^{-\frac{1}{2}}$	

Any combination of terms in the above table can contribute to pp→pX. However for pp→nX the first two terms are not allowed. Furthermore for pp→nX we have $R = \rho$ or A_2 $(I = 1)$ whereas for pp→pX we can have $R = \rho, A_2, \omega$, f exchanges. It is established from two body scattering that the coupling of the ρ and A_2 trajectories to the nucleon vertex is much smaller[5] than that of f and ω $(g_\rho^N = g_{A_2}^N,\ g_f^N = g_\omega^N,\ g_\rho^N \approx 1/5 g_f^N)$. If therefore the first four couplings in Table 1 are sufficient to describe pp→pX we would expect a strong suppression of pp→nX over the region of validity of expansion (1).

Figure 2 illustrates <u>schematically</u> what we should see in this case (for pp→pX we take typical ISR data). If on the other hand we observe comparable p and n production near $x = 0.8$ we must then conclude (in the triple Regge context)

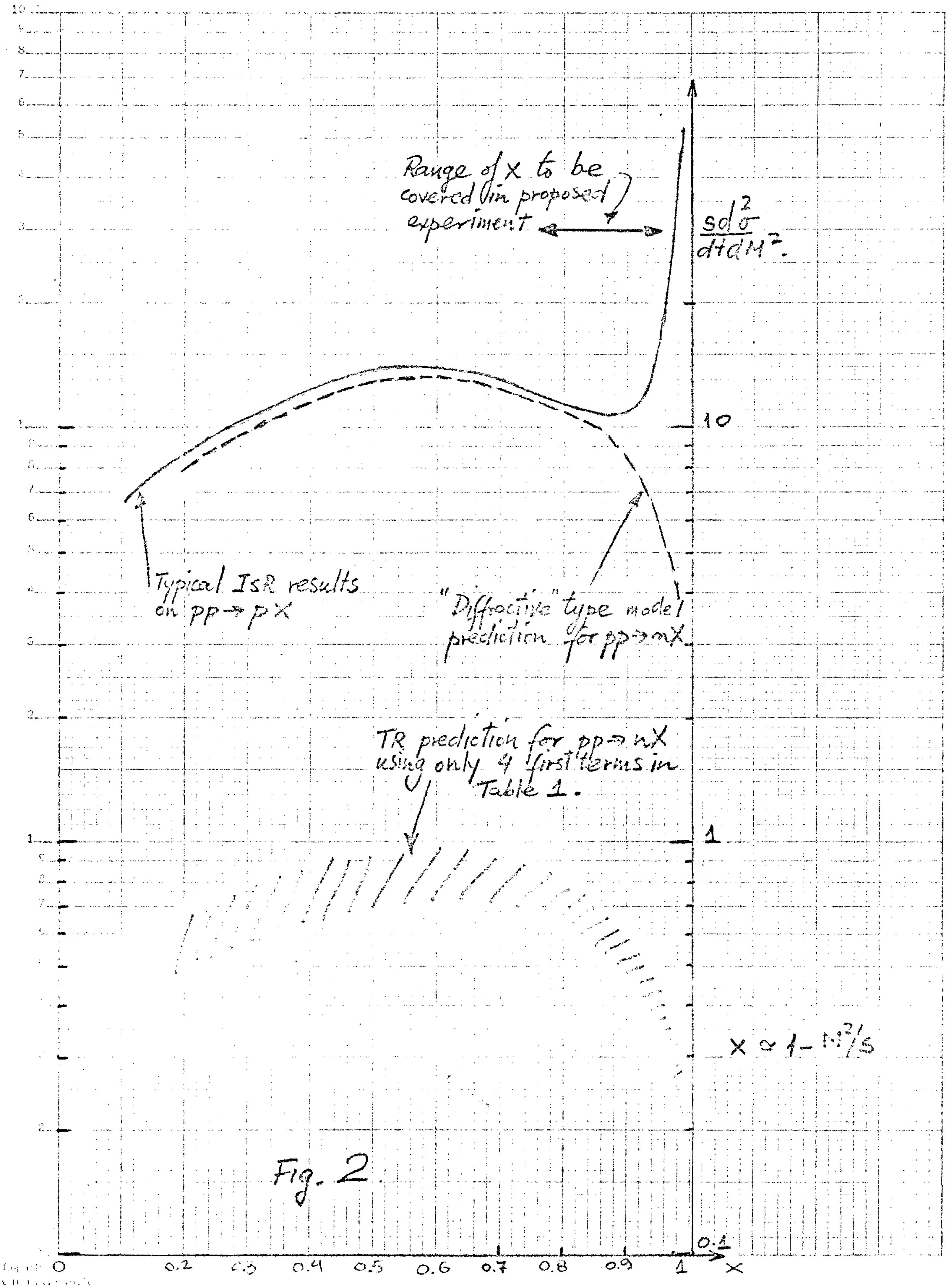

Range of x to be covered in proposed experiment
$\frac{s\,d^2\sigma}{dt\,dM^2}$
10
1
0.1
Typical ISR results on pp → pX
"Diffractive" type model prediction for pp → nX
TR prediction for pp → nX using only 4 first terms in Table 1.
$x \simeq 1 - M^2/s$
0
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
x

Fig. 2

that $\pi\pi P$ and $\pi\pi R$ couplings are very important for $pp \to nX$. Such a behavior would, at best, be considered as "accidental" in the triple Regge framework and would imply that the $\pi\pi P$ and $\pi\pi R$ contributions should not be neglected in fits to $pp \to pX$.

In Fig. 2 we also show the range of x to be covered by the proposed experiment. The rise for $x > 0.85$ can be accounted for either by the PPP or PPR terms in expansion (1). These two terms have different s dependences and we shall be able to determine their relative contributions.

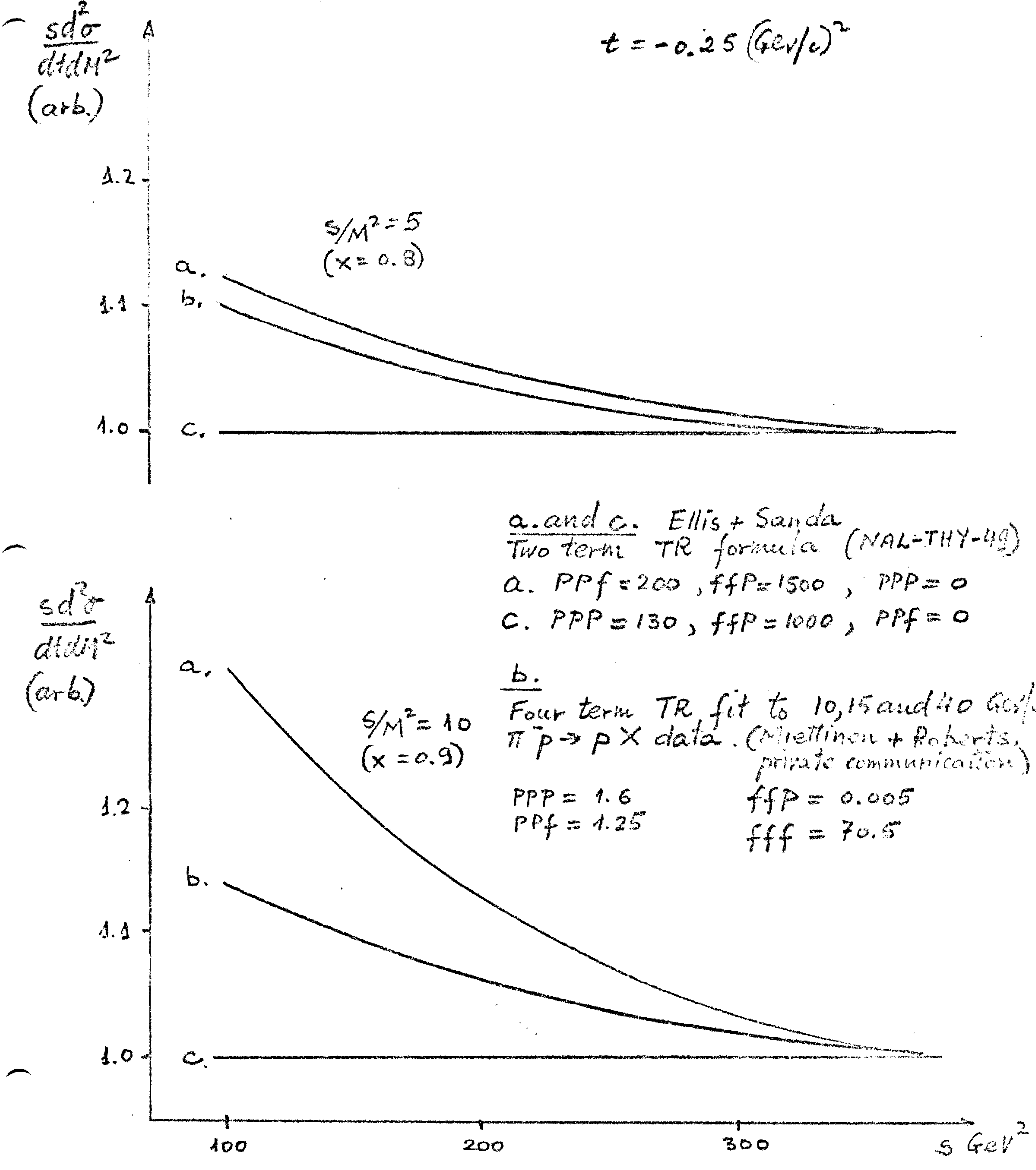
There are many different theoretical conjectures concerning the relative importance of these couplings[6] (mainly related to the interpretation of the Harari-Freund duality scheme) and experimental information would be valuable. Fig. 3 shows some predictions for the NAL energy range based on fits to ISR and sub-NAL energies. The proposed experiment will distinguish among these possibilities.

Diffractive Type Models

In contrast to triple Regge models, Diffractive models predict comparable p and n production[2] for $x < 0.85$. In these models the observed particle spectrum is assumed to come from the three graphs of Fig. 4. Fits to ISR data of

TR predictions for s dependence of $pp \to pX$

$t = -0.25\ (\mathrm{GeV}/c)^2$



a. and c. Ellis + Sanda
Two term TR formula (NAL-THY-49)
a. $PPf = 200$, $ffP = 1500$, $PPP = 0$
c. $PPP = 130$, $ffP = 1000$, $PPf = 0$

b.
Four term TR fit to 10, 15 and 40 GeV/c $\pi^- p \to pX$ data. (Miettinen + Roberts, private communication)

$PPP = 1.6$
$PPf = 1.25$
$ffP = 0.005$
$fff = 70.5$

Fig. 3.

such models[7] indicate that for $x < 0.85$ graphs 4b and 4c dominate the cross section. In this case the recoil particle comes from the fireball or nova cascading to its ground state which is equally likely to be p or n. The rise near $x = 1$ is accounted for by graph 4a.

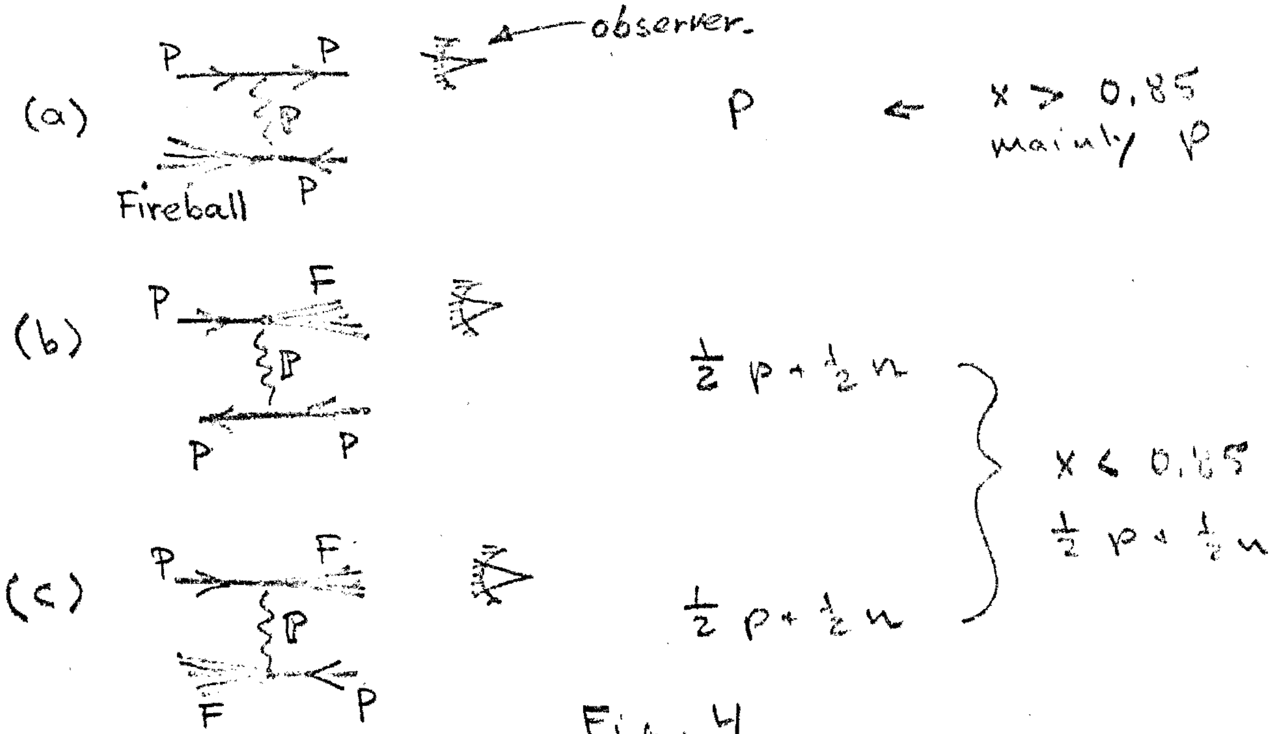


Fig. 4

Summary of Physics Justification

By studying s and s/M^2 dependence of $pp \rightarrow pX$ and $pp \rightarrow nX$ in a limited region of phase space we expect to:

1) Distinguish between "Diffractive" and "Triple Regge" type models.

2) Determine in the triple Regge framework, if it applies, the relative magnitudes of the different possible couplings.

Kinematics

As can easily be shown, at high energy ($s = 2mp_1$), the invariant cross section is proportional to the event rate in a fixed solid angle and recoil momentum bite in the laboratory.

$$\frac{d^2\sigma}{d\Omega dp_c} \propto \frac{sd^2\sigma}{dtdM^2}$$

s/M^2 is essentially fixed by the recoil lab angle and t by the recoil momentum.

$$t = m_b^2 + m_c^2 - 2E_c m_b$$

$$\frac{M^2}{s} = \{1 - \frac{1}{m_b}(E_c - p_c \sin\theta)\} \quad \text{(terms of order } \frac{m^2}{s} \text{ neglected)}$$

Figure 5 illustrates the region we intend to cover in the proposed experiment.

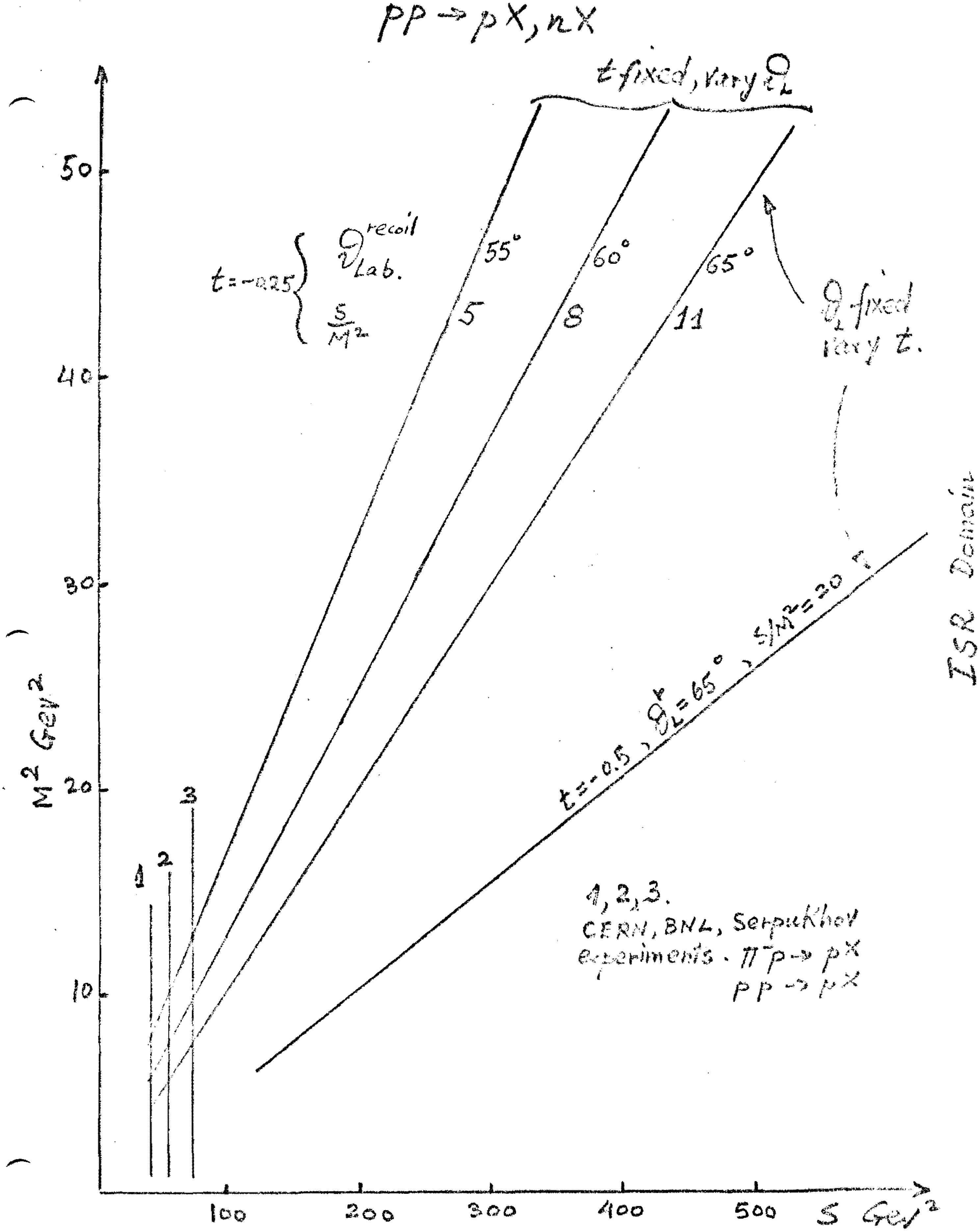

pp → pX, nX
t fixed, vary θ_L
50
40
30
20
10
M² GeV²
t = -.025
θ^recoil_Lab.
s/M²
55°
60°
65°
5
8
11
θ_L fixed vary t.
ISR Domain
t = -0.5, θ^r_L = 65°, s/M² = 20
1
2
3
1, 2, 3.
CERN, BNL, Serpukhov
experiments. π⁻p → pX
pp → pX
100
200
300
400
500
S GeV²

Fig. 5

Experimental Method

The method of detection of the slow recoil protons from the reaction

$$p + p \rightarrow p + X \qquad (2)$$

will be similar to that used in experiment #67, i.e., the protons are identified by range, pulse height and time of flight.

Two techniques will be used to study the physics in

$$p + p \rightarrow n + X. \qquad (3)$$

Reaction (3) can be measured directly by detecting the recoil neutrons produced by protons incident on a hydrogen target or one can study the line reversed reaction

$$p + n \rightarrow p + X \qquad (4)$$

using neutrons in a deuterium target and detecting the recoil protons with the same apparatus used for reaction (2). To extract the neutron information one would need to subtract the effect of the protons in the deuterium and make a Glauber correction. We propose to study all three reactions (2), (3) and (4).

The proposed experiment would run in parallel with NAL experiment #36 (USA-USSR collaboration, pp elastic near 90°) and use a great part of the existing set up of NAL experiment #67 (Rutgers-Upsala collaboration, pp inelastic).

Target

The central feature of the proposed experiment is the use of the circulating proton beam during the acceleration ramp in order to study the s dependence of the cross section. This is made possible by the use of a hydrogen gas jet target located at section C-0 of the main ring at NAL. By pulsing the jet at different times during the ramp it is possible to study all energies between injection (8 GeV) and 300 GeV. The jet target duty cycle (i.e., percentage of the acceleration cycle during which the jet can be pulsed) is limited by the efficiency of the cryopumping system and the gas jet density. A typical figure is 15% for a gas density of 10^{-7} gm/cm^3. This duty cycle allows two jet pulses, each lasting 200 ms, at different energies along the ramp.
In addition to hydrogen, the gas jet target has been succesfully pulsed with deuterium.
The circulating beam profile is an ellipse 2 x 3 mm and with a vertical gas jet about 5 mm in diameter the jet-beam intersection region can be considered as a point source.

The Beam

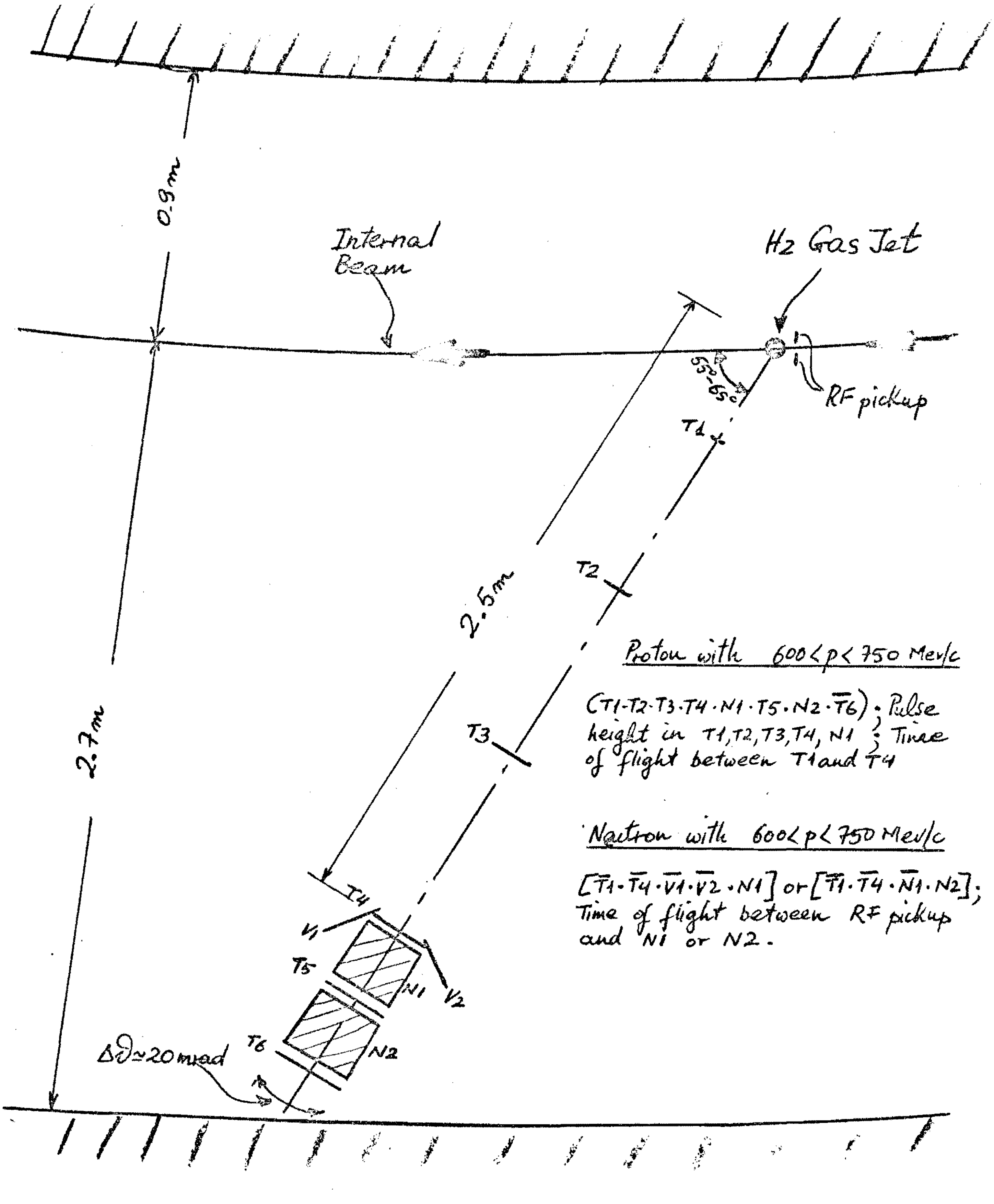
At present the NAL machine operates with single pulse injection. One pulse is ~ 2 μs long and goes around the machine every 20 μs. The RF frequency is 53.24 Mc/s at injection and 53.44 Mc/s at 200 GeV/c. Each beam pulse is therefore separated into about 100 RF bunches each lasting about 1 ns and occurring every 19 ns. This is a crucial point in our measurement of the recoil neutron momentum.

For a jet duration of 200 ms the circulating proton pulse will traverse the target 10^4 times. At present typical single pulse intensities are about $5\text{-}10^{10}$ protons so that $5\text{-}10^{14}$ protons will traverse each 200 ms long jet target pulse. Multipulse injection in the main ring and multiturn injection in the booster are being attempted this month and it is not unrealistic to expect soon an order of magnitude increase in the circulating beam intensity.

The recoil spectrometer

The proposed experiment will be performed inside the main ring and is therefore severely constrained by space and accessibility limitations.

The recoil spectrometer configuration is sketched in figure 6. Slow recoil protons are identified by range, pulse height and time of flight in counters T1 - T6 and N1 - N2. Counters N1 and N2 are tapered scintillator blocks and have a dual function. They are to be used as absorbers for recoil protons from $pp \rightarrow pX$ or $pD \rightarrow pX$ and as detectors for recoil neutrons from $pp \rightarrow nX$. The neutron energy will be



<u>Proton with 600 < p < 750 MeV/c</u>

$(T1 \cdot T2 \cdot T3 \cdot T4 \cdot N1 \cdot T5 \cdot N2 \cdot \overline{T6})$; Pulse height in T1, T2, T3, T4, N1; Time of flight between T1 and T4

<u>Neutron with 600 < p < 750 MeV/c</u>

$[\overline{T1} \cdot \overline{T4} \cdot \overline{V1} \cdot \overline{V2} \cdot N1]$ or $[\overline{T1} \cdot \overline{T4} \cdot \overline{N1} \cdot N2]$; Time of flight between RF pickup and N1 or N2.

FIG.6.

determined by time of flight between one RF bunch and detection in the neutron counters. Typical times of flight between target and neutron counters will be about 6 ns after prompt particles. The neutron time of flight can only be defined modulo 20 ns but this should present no ambiguity as neutrons from the previous RF bunch will not have sufficient energy to trigger the neutron counters.

N1 and N2 will each be about 15 cm long thus leading to detection efficiencies of about 30% for neutrons with kinetic energy $150 < KE < 250$ MeV. Bias levels for these counters can safely be set at 30 MeV so that the detection efficiency will not be sensitive to small changes in the bias. By requiring consistency between neutron spectra in counters N1 and N2 as a function of incident energy one can investigate non neutron triggers which will not necessarily be the same for the two counters.

Backgrounds

Slow recoil proton identification is expected to be easy and clean. Preliminary studies using aluminium absorbers instead of N1 and N2 have shown that this is the case. For neutrons we expect to face three types of spurious triggers. Positive π's and K's stopping in N1 or N2 will be rejected by the prompt vetos but will give delayed triggers from $\pi^+(K^+) \rightarrow \mu^+\nu, \mu^+ \rightarrow e^+\nu$ which will fake real neutrons say 1 μs later. To protect against this the experiment will be inhibited for 3 to 10 μs each time a charged particle stops in N1 or N2.

A second possible source of spurious slow neutron triggers may be fast charged or γ particles reaching the neutron counters indirectly. This problem can only be studied on site and we intend to deal with it by an appropriate combination of veto counters and shielding blocks. The measured singles rates in counters near the beam pipe are quite low and are due almost exclusively to interactions in the target. As the target is a point source it is easy to shield the direct path from target to neutron detectors by inserting tapered lead bricks in the spectrometer. The counting rate in the detectors will then correspond to particles arriving indirectly from the target. The pulsed mode of operation of the jet allows the simultaneous measurement of hydrogen and non-hydrogen events. The point target and pulsed mode are unique properties of the internal target at NAL and they will be fully exploited to identify neutrons from pp interactions.

The third possible cause of backgrounds is K_L^0 particles interacting in the neutron detectors. In the kinematical region of the proposed experiment the ratio $pp \to K_L^0 X / pp \to pX$ is less than 1% so that this possible source of background can be neglected to first order.

Finally, we are also considering the introduction of a small magnet in the recoil spectrometer in order to sweep away charged particles.

Normalization, Luminosity

As the gas jet is pulsed vertically at a fixed radius and as the circulating beam radius changes during the acceleration ramp and also from pulse to pulse there is a need to monitor the luminosity (how much beam hits how much target) in order to normalise the data. This is even more so as the gas jet density changes slowly as a function of time. We envisage three possibilities to do this.

a. Use an array of scintillators in the forward direction surrounding the beam pipe about 10 m downstream of the target which will collect the diffractive part of the total cross section. This monitor will be calibrated using a target made of a thin (7μ) carbon filament mounted on a rotating wheel (60 c/s) and introduced in the circulating beam from below when the jet is not in operation. With this target configuration we can ensure that the carbon filament intercepts fully the beam and we can calibrate the forward monitor against the circulating beam current.

b. Measure the rate of a calculable process such as $ep \rightarrow ep$. The kinematics for this process is such that at 45° in the lab. one has 1 MeV electrons which can be identified by a solid state detector telescope.

c. Normalise all rates to the rate of slow $\pi^{\pm}$ in the recoil spectrometer itself. As has been shown by several experiments below 30 GeV and at ISR the invariant cross section for $pp \rightarrow \pi^{\pm}X$ scales in quite a large region of s/M^2. In terms of the Feynman variable $|x| \simeq 1 - M^2/s$ the cross section is independent of s for $.15 < |x| < .85$.

The range of x covered by our spectrometer for the above reaction is $.14 < |x| < .18$ which is just at the limit of the scaling region. In fact in this range of x the cross section for reaction $pp \rightarrow \pi^{+}X$ is independent of s but that for $pp \rightarrow \pi^{-}X$ has a non scaling component. As we cannot distinguish between $\pi^{\pm}$ we must rely on other experiments to get the weak s dependence of $pp \rightarrow \pi^{\pm}X$.

Of the above three possibilities c. is the simplest to implement and the most attractive as it automatically takes into account possible s dependent changes in the spectrometer acceptance (for example vertical movement of the beam as a function of s). Possibility b. will probably be explored by NAL experiment #36 (pp elastic at 90°). We also intend to investigate possibility a. If a. or b. can give a reliable monitor of the luminosity our data on $pp \to \pi^{\pm}X$ can be used to derive physics information. However, as we want to keep the proposed experiment short in time and simple we may have to rely on $pp \to \pi^{\pm}X$ for normalisation.

Event rates

Preliminary test runs with the equipment of NAL experiment #67 have given very useful information on proton event rates.

For reaction $pp \to pX$ and for:

-1 jet pulse lasting 200 ms during ramp ($170 < p_1 < 190$ GeV/c)

-4.10^{10} protons/beam pulse

-$550 < p_{recoil} < 650$ MeV/c

we get 2 recoil protons.

In the near future the circulating proton intensity is expected to increase by an order of magnitude (multipulse injection in main ring + multiturn injection in booster). Assuming 10^{11} circulating protons, 30% neutron detection efficiency, $\sigma(pp \to nX) \sim \frac{1}{3}(pp \to pX)$ in our kinematical region, we need 200 hours of running to cover 20 energy intervals and 4 values of s/M^2 with 5% statistics for $pp \to nX$ and 1.5% statistics for $pp \to pX$.

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5) V. Barger and R. J. N. Phillips, Nucl. Phys. B32, 93 (1971).

6) For example: M.B. Einhorn, M. B. Green, M. A. Virasoro, Phys. Letters 37B, 292 (1971) deduce from a dual model that the PPf coupling should vanish. Ellis and Sanda in ref. 4) make the conjecture that the PPf and ffP terms should dominate.

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