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# PROTON-PROTON INTERACTIONS ABOVE 100 GeV

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ABSTRACT

In an experiment at Echo Lake, Colorado a detector consisting of an ionization calorimater, spark chambers, and a 2000 liter liquid hydrogen target has been operated to collect over $10^5$ triggers corresponding to greater than 80 GeV calorimeter events. Quantities being studied include multiplicities, angular distributions, and total inelastic cross sections. Preliminary results give an average multiplicity of secondaries from hydrogen interactions of hadrons about 70% of that from carbon interactions in the 100-400 GeV energy range.

An experiment has been operated at Echo Lake, Colorado (3200 m) over the past year with the objective of determining the proton-proton cross section in the energy range from 50 to 1000 GeV. As analysis of the data from this experiment is still in progress, we present here a progress report on this work.

The experiment (Fig. 1) consists of wide-gap spark chambers on either side of a liquid hydrogen target, all placed above a large ionization calorimeter, containing in its upper layers iron-plate spark chambers. The wide gap chambers have an area of 2.0x2.0 $m^2$ and each contain two gaps of 20 cm. The electrodes are of 50μ hardened aluminum. A pulse voltage of about 100 kV is supplied by Marx generators to the center electrode of each chamber on receipt of a trigger. The target has a capacity of about 2000 liters of liquid hydrogen. It is in the shape of a short vertical cylinder with thin domes of spherical sections. The outer vacuum jacket domes are of 6.6 mm aluminum and the inner hydrogen flask domes are of 1.2 mm stainless steel. Hydrogen loss from the target was about 65 liters per day, so that every ten days the target was refilled after boiling off about one third of its volume. The central thickness of the filled target is 80 cm, and the average path length of a proton through the liquid hydrogen during the experiment was about 55 cm. Elaborate safety precautions were employed during the

7 months of continuous operation with hydrogen in the target. Below the lower wide gap chamber are 200 g $cm^{-2}$ of iron made up of twenty 13 mm copper-clad steel plates of $2.0x2.5m^2$ assembled as a 10-gap conventional spark chamber (2 cm gaps) with two plates (20 g $cm^{-2}$) between gaps. Below this is a stack of 75 tons of steel of 2.5x2.5 $m^2$ area. Including the iron of the iron-plate chamber, this provides a calorimeter of a total of 1120 g $cm^{-2}$ of iron. Interspersed among the iron plates are 10 layers of plastic scintillator, each viewed by 8 photomultipliers. The counter layers lie at depths in the iron of 40, 120, 200, 320, 440, 560, 680, 800, 960, and 1120 g $cm^{-2}$ of iron. The admittance of the system is approximately 1 $m^2$ sr.

A "guard ring" of anticoincidence counters of total area about 10 $m^2$ surrounds the mid-plane of the target spaced about 20-50 cm radially from the target. This suppresses spurious triggers due to air showers, etc.

In operation, a summed signal from the ten calorimeter counters triggers an "event" when an energy corresponding to (nominally) greater than 84 GeV is deposited, together with a pulse from a 1.8x1.8 $m^2$ counter at the top of the apparatus and no pulse from the shower anticoincidence ring. This fires the spark chambers and records the pulse heights of each of the 10 counter layers on magnetic tape. The chambers are photographed with 50:1 demagnification by two 35 mm chameras each recording one of two orthogonal, horizontal views of the several spark chambers. Mirrors are used to collapse the optical path and to condense the vertical space on film. A sequential event number and other run information is recorded (in binary code) on both films and on the magnetic tape record. Other trigger modes were employed for shorter portions of the run, e.g., operating with a threshold reduced to about 34 GeV.

An event was recorded on an average once every three minutes. From the hydrogen run, 145,000 events have been collected, including 85,000 with 84 GeV trigger threshold and 43,000 with 34 GeV threshold. Periodic calibration of the calorimater layers was made using muons, with a calibrated amplifier in each line, and the response function of each logarithmic analog digital converter was calibrated.

Prior to the liquid hydrogen run a run was taken using a 17 g $cm^{-2}$ carbon target. This shorter run collected about 25,000 events.

Analysis of the total data sample is now in progress. Of all triggers, 50-7-% are useful for analysis (e.g., contain only one incident hadron in the spark chambers). The film is scanned by physicists for useful events and recorded as to "straight through" or target interactions. The target interactions are digitized on conventional manually-operated measuring machines while the "straight through" events are digitized on a computer-connected programmed-spot automatic system (the Michigan Automatic Spark System). Magnetic tape from the film measurements is combined with the pulse height record from the calorimeter to obtain a summary tape containing for each event a record of the total energy, path length in liquid hydrogen, track coordinates (angles and intercepts), and information on angles, etc. of secondaries where appropriate. Film is digitized to a precision of 10μ (manual bubble chamber digitizers). The resolution corresponds to a 4 mr equivalent scattering angle, however this appears to be predominantly due to systematic distortions in the optical system which are being removed in the analysis through the use of a precise fiducial grid photographed at the plane of the front face of the chambers.

As of August 1969, all of the carbon film has been digitized, yielding over 12,000 non-interacting tracks and about 1500 interactions. Less than half of the hydrogen film has been digitized, yielding over 50,000 straight tracks and 2500 interactions. Rescanning and remeasurement are only just begun. This is particularly important for multiparticle final state interactions, where a criterion on minimum $\chi^2$ rejects events in the computer when digitizing errors are made.

The apparatus at Echo Lake is now being modified through the installation of a split target of iron and aluminum in order to measure cross sections on these elements. Each target is in the form of 6 plates, each of about 3% of an interaction mean free path, and spaced by 15 cm to permit separation (by vertex reconstruction) of secondary interactions and gamma showers from the primary interactions. At a later time a target of lead and tin will be installed.

The objectives of the experiment are 1) to measure the total inelastic proton-proton cross section from 50 to 100 GeV, 2) to study the A-dependence of the cross section at different energies as well as the A-dependence of multiplicities, 3) to study multiplicity distributions from pp interactions vs. E, and 4) to study angular distributions vs. E. In addition, further understanding of the ionization calorimeter technique and of the development of nucleon cascades in thick materials will be a practical byproduct.

Several factors have prevented the obtaining of preliminary cross section values at this time. The production of an energetic delta-ray simulates a two-prong inelastic interaction in our detector (as no magnetic field is present). As an example, the carbon target corresponds to 18% of an interaction mean free path for nuclear interaction, however we expect (and qualitatively see) about a 10% probability for production of a $\delta$-ray of over 2 MeV. Fortunately, the multiple coulomb scattering of the $\delta$-rays is sufficient to reject most of them on the scanning table. However we expect a few per mil of the traversals to produce $\delta$-rays of over 300 MeV which would correspond to about a 2% uncertainty in cross section determinations and must be eliminated by calculation. This $\delta$-ray problem is present and must be considered in any very high energy experiment where no magnetic field is used. From our hydrogen data we find that 60% of the 2-prong events show an obvious $\delta$-ray scatter, 15% are consistent with a genuine 2-prong hadron reaction, or with production of a $\delta$-ray of several hundred MeV.

That the calorimeter response is a function of whether or not the incident hadron interacts in the target is evident from the (preliminary) energy spectra of interacting and non-interacting particles and from the anomalously low cross sections which would be inferred from only scanning criteria. By studying energy spectra, energy loss profiles, and calorimeter response as a function of the vertex depth in the Fe plate chambers we may extrapolate back to interactions in the target and so correct for this effect. This rather time-consuming program is not yet accomplished.

About 5% of the straight tracks in a given energy bin will be due to electromagnetic interactions of $\mu$'s in the calorimeter. This effect can be readily calculated and corrected for.

The ratio of protons to protons plus pions in our range of energies is 0.67 ±0.10. This corresponds to an error of ±2 mb in the pp cross section, assuming that the pp and $\pi p$ cross sections remain in the ratio of 3:2 at our energies. This pion flux does not consider the effect of anticoincidence counters; in our particular experiment relatively more pions than protons may be rejected by the elimination of hadrons accompanied by showers. We expect to study this effect with a threshold Cherenkov counter incorporated into our apparatus at a later date.

At accelerator energies, 20%-25% of the total cross section corresponds to elastic scattering. At 100 GeV, the most probable angle for pp elastic scattering is about 2.2 mr (corresponding to $d\sigma/dt \propto \exp 10t$), hence it will be difficult for us to resolve elastic scattered protons except near the lower end of our energy range. Consequently most of our information concerns $\sigma$(absorption), not $\sigma$(total).

In view of the falling cosmic ray spectrum only a few percent of our events lie over 500 GeV, hence our cross sections will be limited by statistics to about ±10% uncertainty above that energy range. Below 200-300 GeV it is probable that the sytematic problems already alluded to will limit us.

The angular distribution of secondaries is being studied in a somewhat unconventional manner. The digitization of secondaries from interactions makes no attempt to correlate tracks between views, rather the two orthogonal projections of each event on a plane containing the incident track are considered separately. A modification of the Duller-Walker plot is constructed for all events in each particular energy bin. We have found that

$$F^2(\theta_p)/(1-F^2(\theta_p)) = \gamma^2 \tan^2 \theta_p$$

for an isotropic c.m. distribution, where $\theta_p$ is the angle between the projection of a secondary and the incident particle in a plane containing the incident particle. Curves of other values of $\ell n(F^2/1-F^2)$ vs. log tan $\theta_p$ have been obtained for various parameters of a c.m. angular distribution corresponding to a general form:

$$a + b \cos_n \theta_c.$$

Multiplicity distributions require correction for $\delta$-ray contamination, not only for 2-prong events, but for $\delta$-rays produced by secondaries from inelastic hadron collisions. This second effect is a small (less than 5% bias) on average multiplicities. The carbon target contains 0.21 radiation lengths of material between the target mid-plane and the lower chamber and the hydrogen target contains 0.19 r.l. Hence in each case some of the secondaries are electron pairs from $\gamma$-ray conversions. The effects should be essentially the same in both targets.

To date the most interesting quantitative result is the comparison of average multiplicity at each energy between carbon and hydrogen. This difference (Fig. 2) is quite independent of systematic uncertainties which are substantially the same for carbon and hydrogen. For example the details of what fraction of the remaining two-prong events are high energy $\delta$-rays would not significantly effect these numbers. The events with vertices in the metal walls of the hydrogen target are of course excluded. While this result is very preliminary we have found no reason to doubt its validity.

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## Figure Captions

Figure 1. Topology of the Echo Lake experiment.

Figure 2. Average multiplicities from hadron interactions in carbon and in liquid hydrogen between 100 and 400 GeV. The errors are statistical only.

Total Cross Section Experiment

Front View

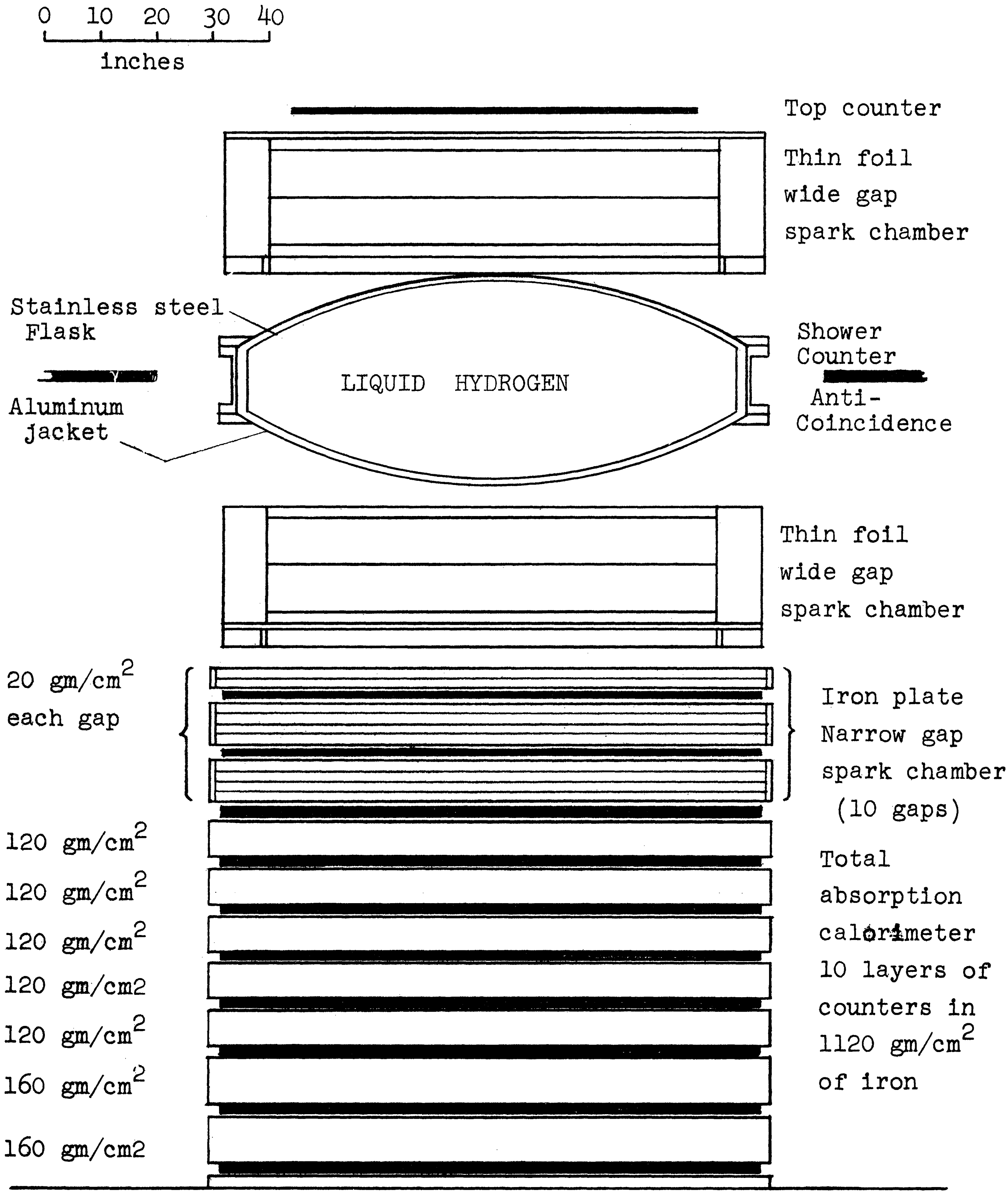
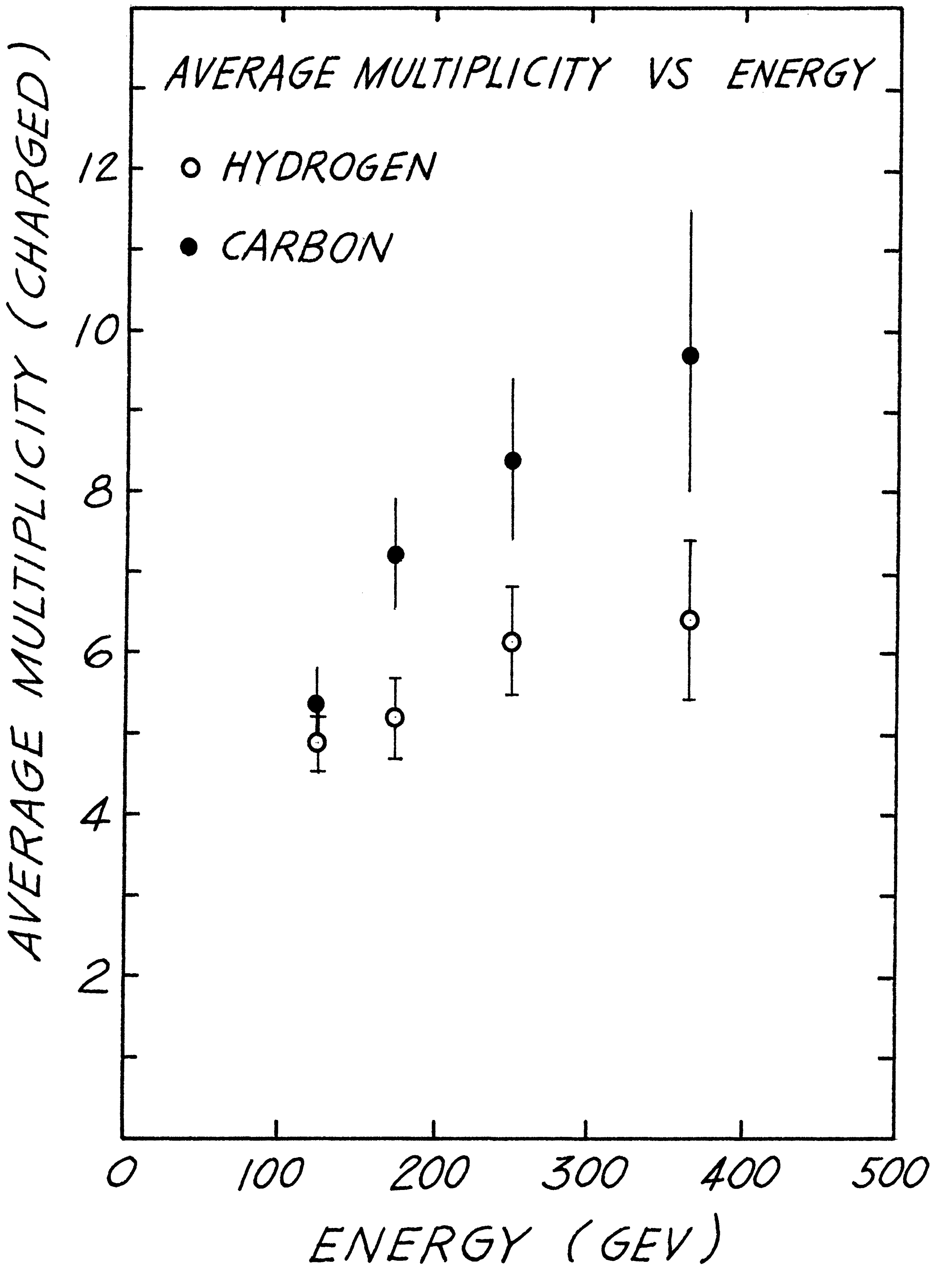



Figure 1



AVERAGE MULTIPLICITY VS ENERGY
o HYDROGEN
• CARBON
AVERAGE MULTIPLICITY (CHARGED)
12
10
8
6
4
2
0
100
200
300
400
500
ENERGY (GEV)


Figure 2