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PROPOSAL TO STUDY MULTIPARTICLE PRODUCTION WITH NAL BUBBLE CHAMBER

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ABSTRACT

We propose an extensive energy-dependent survey of pp, πp, and to a lesser extent, Kp and $\bar{p}p$ interactions in the large NAL bubble chamber. Both positive and negative unseparated beams would be used and individual particles would be tagged and their positions recorded with a combination of Cerenkov (or possibly transition radiation) counters and wire chambers. Results from cosmic-ray and accelerator experiments have revealed many interesting regularities in particle production from hadron collisions and have been clarified by various theoretical ideas including the limiting fragmentation hypothesis of Yang and co-workers, the parton model of Feynman, Regge phenomenology, and various versions of the multiperipheral model. These models, and unitarity considerations in general, emphasize the need to study all reactions rather than concentrate only on specific channels. With current and projected bubble chamber analysis techniques we can adequately analyze several hundred thousand events within a period of less than two years after pictures are taken. Our requirements are summarized below:

1) Pictures and Momenta -

	P_{max}	$\frac{2}{3} P_{max}$	$\frac{4}{9} P_{max}$
Positive	200K	400K	200K
Negative	200K	200K	200K

The momenta chosen are those appropriate to a test of quark-model predictions of relations between πp and pp cross sections.

2) Number of Events -

1 event/picture or 1.4×10^6 events.

Number to be measured depends on exploratory scans.

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PHYSICS JUSTIFICATION

1. Outline of Experiment

The members of this collaboration have been involved in bubble chamber research on 29 GeV/c nucleon-nucleon (BNL and Vanderbilt)[1] and 25 GeV/c pion-nucleon (Wisconsin)[2] interactions, the highest machine energies in this country prior to the NAL accelerator. The experiment now proposed is an extension of those researches to NAL energies.

This extension entails a comprehensive study of hadron-hadron interactions with the NAL hydrogen-filled bubble chamber. The proposed research seeks to investigate the whole range of inelastic channels, primarily in pp and πp interactions, at several incident energies up to the highest available. A total of 1.4 million pictures is requested.

Most hadron-hadron interaction experiments at present accelerator energies involve studies of relatively simple low-multiplicity reactions that account for only a small fraction of the total cross section. It is more difficult to gather data on all channels than to concentrate on a few final states which yield concise information, such as resonance production or structure in a differential cross section. However, to complete our understanding of strong interactions from hadron-hadron collisions, we must include all inelastic channels in order to tie the various equations in any theory together, as required by unitarity. Furthermore, at very high energies we know that many channels are opened up and high-multiplicity final states account for the major part of the cross section, thereby requiring new methods of organizing and plotting the data, which include high multiplicities.

Recently, both Feynman and Yang and his co-workers have stressed the importance of studying the limiting behavior in particle distributions resulting from high energy collisions.[3,4] Their suggestions require that measurements be made of momentum spectra from all contributing channels instead of taking data only on specific final states.

In view of the above-mentioned considerations, we propose this study of hadron-hadron interactions.

To study limiting behavior with a given beam and target particle, we will need data at more than one energy besides the highest available energy. It is of interest also to compare interactions between different types of particles. This leads us to suggest that exposures be taken with both positive and negative unseparated beams and to tag beam particles individually by electronic means. In this way studies can be made of pp, $\pi^- p$, and $\pi^+ p$ interactions as well as $K^\pm p$,and pp at momenta where their flux is appreciable. In choosing the values of beam momenta, we use the prediction that multiplicities may vary according to $\ln(P_{LAB})$ and also the quark model prediction that pp cross sections are quantitatively related to πp cross sections at two-thirds the pp laboratory beam momentum. In addition, it would be desirable to have $\pi^- p$ and pp data at the same energies for other comparisons, such as studies of the target proton "fragmentation" as described by Yang. These considerations lead us to choose the momenta P_{max}, 2/3 P_{max}, and 4/9 P_{max}, where P_{max} is the maximum available momentum for both negative and positive unseparated bubble chamber beams.

In the following sections we include information on previous experiments, theoretical background, objectives of this experiment, and finally, experimental techniques and requirements.

2. Previous Experiments

Results from both cosmic-ray and accelerator experiments give us guidelines and motivation for detailed studies of high energy collisions in the NAL energy range.

2.1 Cosmic-Ray Experiments: Beginning with cosmic-ray data,[5] we learn the following:

(1) The transverse momentum of produced particles remains small, $\leqslant 1$ GeV/c, for incident momenta up to several thousand GeV/c. Multiplicities tend to increase as $\ln(P_{LAB})$, although statistics are poor and $E^{1/4}$ dependence is not ruled out.

(2) Total cross sections appear to be roughly constant, although some recent Russian data show $\approx 20\%$ increase in proton-carbon cross section up to ≈ 1000 GeV/c.

(3) No definite conclusions can be reached regarding the distribution of particles since the momentum of fast particles cannot be determined; however, the data are consistent with the picture that there are high momentum forward and backward jets in the center-of-mass plus a component of low-momentum pions labelled "pionization."

(4) In the 1000 GeV/c range, a large K/π ratio, as well as other measurements, leads to the conjecture that a particle of mass ≈ 2 GeV called the "Aleph" exists and decays $\approx 70\%$ into (nucleon + φ) and $\approx 30\%$ into (nucleon + η'). This Aleph is said to play a dominant role in these very high energy collisions, although much better data are needed to confirm its existence.

2.2 Accelerator Experiments: Accelerator data are of a much more detailed nature, although at a much lower energy and spanning a much narrower range of energies than cosmic rays. Interesting regularities have been seen in the data which pose questions for higher energy experiments.[6] Some detailed studies lead to the following conclusions:

(1) Cross sections for two-body and quasi two-body reactions obey a power law behavior; i.e., $\sigma \approx 1/P^{\alpha}_{LAB}$, where $\alpha \geq 0$. The magnitude of α depends on the nature of the internal quantum numbers exchanged

in the t-channel. In the special cases where no quantum numbers are exchanged, $\alpha = 0$ and cross sections are constant with energy. These channels are usually interpreted as the "diffraction dissociation" of beam and/or target particles.

(2) The differential cross sections for two-body and quasi-two body channels reveal interesting dips and changes in exponential slope which vary as a function of energy and need further study at much higher energies. In pp elastic scattering the structure seems to become more pronounced as energy increases from 3 to 30 GeV.

(3) Apart from the above-mentioned behavior of two-body or quasi two-body final states, there are no simple rules we can state about particle production. For example, in 30 GeV/c pp collisions it is impossible to determine whether there is pionization, as inferred from cosmic-ray experiments. Low-momentum pions in the center-of-mass are produced just as easily by isobar decays, or in more general terms, by fragments of the colliding protons. It is hoped that higher energies will make it possible to separate out distinct components in multiparticle final states.

(4) At energies up to 25 GeV/c, in $\pi^- p$ collisions the strange particle cross section rises sharply, making possible more general studies of multiple meson production.[2] Single particle distributions for different kinds of particles, as well as more varied resonance production, provide a wider range of data to confront theory.

3. Theory

Although no rigorous theoretical framework exists for particle production in hadron-hadron collisions, there are several common features and predictions from the most current models. The following models, in our opinion, are the most relevant to our studies of high energy collisions.

3.1 Limiting Fragmentation: The hypothesis of limiting fragmentation[3] of Yang and co-workers tells us that in the high energy limit the beam and/or target particles fragment into two separate clusters of emerging particles, e.g., $p + p \rightarrow p + p^\dagger$ or $p^\dagger + p^\dagger$, where $p^\dagger$ is a cluster. These clusters preserve the internal quantum numbers of the fragmented particle, target or beam. The concept of diffraction dissociation of Good and Walker is implicit in the fragmentation hypothesis. Furthermore, Yang and co-workers emphasize that the proper frames of reference in which measurements are to be made are the rest frames of the beam or target particles. For example, the momenta of the target proton fragments approach limiting distributions when viewed in the laboratory system. No prediction is made concerning distributions in other rest frames and in particular, as a separate hypothesis, Yang and co-workers argue that pionization does not exist.

3.2 Parton Model: Feynman's approach[4] to high energy collisions has a common feature to that of Yang and co-workers in that high energy limiting distributions are expected. However, he makes some additional specific predictions. The parton model has features similar to electrodynamics, in that at sufficiently high energies particles can be produced without taking away much energy from the "leading particles" in the collision. In this way soft hadrons are put on the same footing as bremsstrahlung in electrodynamics. Several predictions follow:

(1) Unlike Yang and co-workers, Feynman favors the overall center-of-mass for viewing distributions. He suggests the variables x and Q^2, where $x \equiv (P_L$, longitudinal momentum$)/(P_{L,\ \max}$, maximum longitudinal momentum) and where $Q^2 \equiv (P_T$, transverse momentum$)^2$, for plotting particle distributions.

(2) For x "small", i.e., $1 \gg x \geqslant 1\ \mathrm{GeV}/P_{L,\ max}$, the distribution in x is $dN/dx = 1/x$ and should be energy independent. For $x \leqslant 1\ \mathrm{GeV}/P_{L,\ max}$ no prediction can be made for the distribution of particles. The latter are termed as "wee" momenta and represent the pionization component.

(3) Predictions are made for the energy dependence of high momentum single particle distributions independent of other particles in the final state (inclusive reactions) and for specific final states (exclusive reactions). These predictions are related to the usual Regge power law behavior.

(4) As in the multiperipheral model, below, average multiplicities are expected to vary $\approx \ln(P_{LAB})$ and distributions of multiplicities at given energies are Poisson distributions.

3.3 Multiperipheral Model: The multiperipheral model has been cast in many specific forms for purposes of fitting data.[7] However, there are some general predictions that would apply for any version of the model. The essential assumption of multiperipheralism is that the amplitude is a product of several independent terms, each representing a particle or Reggeon exchange. The immediate predictions that follow have to do with the variation of multiplicities with energy; i.e., $\bar{n} \approx \ln(P_{LAB})$ where $\bar{n}$ is the mean multiplicity. The model also implies that the multiplicities at a given energy are Poisson distributed. Any particular version provides more detailed predictions concerning dependence of various channels on the appropriate kinematic variables.

3.4 Quark Model: Satz[8] has formulated an additive quark model together with an isospin distribution of charge configurations to give one-to-one connections between multipion final states from NN and πN reactions. The laboratory momenta at which to compare cross sections are chosen in the ratio $P_{LAB}^{N}/P_{LAB}^{\pi} = 3/2$ for an equidistribution of momenta among the three (two) quarks of the incident nucleon (pion).

4. Objectives of Experiment

The experimental results and theoretical ideas outlined in the previous sections suggest that we make the following studies:

(1) Measurements of energy dependency are crucial for any theory. We will want to examine the energy dependence of single particle distributions (inclusive reactions) as well as study specific final states. Regge power law behavior can be tested for two-body channels. In particular, the role of diffraction dissociation at high energies should be studied. A minimum of three energies is desirable, including the highest available. With good statistics, we can examine the relationship between multiplicity and momentum (see Section 3).

(2) It is desirable to study as many different types of hadron-hadron interactions as we can. Comparisons between pp, πp, Kp, and $\bar{p}$p are of fundamental importance since we expect that the various channels are quantitatively related. We will want to test quark model predictions that cross sections for final states in pp reactions are related to those of πp reactions at two-thirds of the pp energy. These considerations lead us to suggest taking both positive and negative beams at momenta P_{max}, 2/3 P_{max}, and 4/9 P_{max} where P_{max} is the maximum momentum at which both positive and negative bubble chamber (unseparated) beams are available. The identity of specific particles can be tagged individually (see next section).

(3) We would like to get a picture of what particle production looks like in the overall center-of-mass. Does pionization exist? It is not clear that we will necessarily be able to separate forward and backward jets from a pionization component, but this will be interesting to examine. Feynman's predictions about the spectrum

in the variable x will be interesting to test. Good statistics on multiplicities at a given energy, with estimates of π^o production, will enable us to make much more accurate comparisons with theory than cosmic-ray results. At these energies, anti-particle production may become very abundant (although Serpukhov results do not show this trend), and perhaps some undiscovered anti-particle states will be seen.

(4) There may be many surprises. If quarks happen to be produced with large enough cross sections we would naturally want to learn all we can about them. The Aleph of cosmic-ray experiments may show up at the highest energies we study. There are other things, though less dramatic, that will be of interest.

(5) Other bosons besides pions are certainly produced to a significant degree and data on high-energy reactions should help determine the role of ρ, ω, K, K^*, and higher-mass bosons in hadron interactions, both with and without strangeness transfer. The degree to which well-defined baryon resonances take part must also be determined to have a complete picture of these phenomena.

EXPERIMENTAL ARRANGEMENT AND SPECIFICATIONS

1. Bubble Chamber Specifications

The bubble chamber planned for NAL with a length of 3-4 meters and a field of 15-30 kG should be suitable for our experiment. Reports from the NAL summer study programs discuss problems associated with bubble chamber studies of strong interactions at very high energies.[9] We outline below our expectations regarding what can be done with the NAL bubble chamber in terms of the measurements required for the studies we propose.

1.1 Single Particle Distributions: Good momentum determination of fast tracks is needed to isolate "leading" particles from slower secondaries. We can obtain $\frac{\Delta P}{P} \leqslant 10\%$ for 200 GeV/c particles with a track length $\geqslant$ 2 meters, setting error $\leqslant 200\ \mu$, and field $\approx$ 20 kG. This should be good enough for our purposes. A small chamber would not have the track length to meet minimal requirements; i.e., to distinguish the highest momentum secondaries from the intermediate momenta.

1.2 Specific Final States: Experience with data from the BNL 80-inch bubble chamber at $\approx$ 30 GeV/c has taught us that the only specific final states that can be reliably identified are those in which no missing or neutral particles are produced and for which four-constraint kinematic fits can be made.[1,2] Whether it will be possible to obtain a large fraction of unambiguous four-constraint fits at $\approx$ 200 GeV/c will depend in part on the setting error that will apply to the NAL bubble chamber. We expect that there will be cases involving single π^o's with small longitudinal and transverse components of momentum in the laboratory which make good kinematic fits without including the π^o. However, based on our success with the BNL 80-inch bubble chamber data at $\approx$ 30 GeV/c and based on some independent calculations presented at the NAL study program,[9] we expect that a large bubble chamber with good accuracy ($\leqslant 200\ \mu$ setting error) will permit unambiguous four-constraint fits to > 50% of final states with no neutral or missing particles. The ambiguous cases can be resolved to some extent by detailed studies such as requirements of forward-backward symmetry in pp interactions.

1.3 Detection of Gamma Rays: A complete program for the study of multiparticle production might eventually include the use of a track-sensitive target in a neon or neon-hydrogen mixture.[10] By the time a reasonable bubble chamber facility becomes available, such targets are likely to be well tested. At that time we may wish to reformulate our proposal somewhat.

1.4 Missing Mass Calculations: In deriving missing masses from recoil protons, multiple scattering limits the precision on angle measurements. For example, with a 200 GeV/c beam and a recoil proton of $\approx$ 300 MeV/c, assuming a missing mass (MM) $\approx$ 1 to 2 GeV and an angular uncertainty $\delta\theta \simeq 0.5^\circ$, the error δ(MM) $\simeq$ 1 GeV. This error, although large, allows valuable gross studies of diffraction dissociation.

2. Beam

It is our objective to study mainly pp and πp interactions at several energies. We will use both positive and negative unseparated beams and tag individual particles by using a combination of either a Cerenkov counter or a transition radiation counter for particle identification and wire spark chambers to record beam particle location.[11] In this manner we select protons and π^-'s at all energies, and π^+'s, and to a much lesser extent $K^\pm$, $\bar{p}$, at the lower energies. It will be important to use wire or Charpak chambers for the additional purpose of accurately defining the beam direction.[9] This would be desirable because it would make it possible to take a very short beam-defining region in the bubble chamber, thus allowing a larger fiducial volume for interactions. Good beam-momentum accuracy is obviously desirable, i.e., $\frac{\Delta P}{P} \leqslant 0.1\%$.

3. Momenta and Numbers of Pictures

The following numbers of pictures and momenta are requested. P_{max} designates the maximum momentum available to the bubble chamber for which both negative and positive beams can be obtained. The factor 2/3 is used to compare predictions of the quark model, which relates pp at momentum P to πp at momentum 2/3 P.

Beam	P_{max}	2/3 P_{max}	4/9 P_{max}
Positive	200K	400K	200K
Negative	200K	200K	200K

The larger number of pictures at 2/3 P_{max} for positive beams is so that we insure an adequate sample of π^+'s at this momentum, since the π^+/p ratio is expected to be $\approx$ 5%. An average of only one event per picture is desired to avoid confusion in scanning and measuring. This gives 1.4×10^6 events in the experiment; the number to be measured depends on preliminary scans.

4. Data Processing

Our groups have already carried out extensive studies of pp and πp interactions at $\approx$ 30 GeV/c. Nearly all interactions up to the highest multiplicities and including events with strange particles have been measured in our past experiments. These amount to approximately 100,000 events in the Wisconsin π^-p experiment and > 100,000 events at Brookhaven, including the new pd experiment currently being carried out as a Brookhaven-Vanderbilt collaboration. Improved data processing will enable even greater numbers of events to be measured, especially with Thompson's three-dimensional device (SATR) at Wisconsin.[12] The same types of analysis programs will be used as in our past studies.

APPARATUS

1. Bubble Chamber

This proposal is for the planned NAL bubble chamber of about 30 cubic meters volume with 3-4 meters along the beam line and 15-30 kG magnetic field, as outlined in the March 27, 1970 memo to users from R. R. Wilson.

2. Beam

One of us (R. Panvini) will take part in the 1970 NAL Summer Study program. Design problems can be worked out at that time.

3. Analysis Facilities

3.1 Brookhaven National Laboratory: Brookhaven currently operates with two HPD's and measures about 500,000 pictures a year. With minimum guidance in operation, this figure will later be raised to about 1,000,000 pictures a year. Existing computer programs have been used to process complex high multiplicity events and will be suitable for the proposed experiment.

3.2 Vanderbilt University: Vanderbilt has six high precision image plane digitizers which can be used for final measurements, if necessary. At present, these digitizers are being used to make roads for HPD measurements.

3.3 University of Wisconsin: Wisconsin has six film plane digitizers on line to a 924 computer. The measurements are fed into the same basic geometry program used by the current BNL-Vanderbilt collaboration. It is expected that within a year the Wisconsin-developed SATR device[12] will pre-scan and measure bubble chamber film and should substantially increase Wisconsin's capability for handling large numbers of complicated event topologies.

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