High Energy Heavy Ion Collisions--A Possible Testing
Ground for High Energy Interaction Models*

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ABSTRACT

A review of existing data on nucleus-nucleus collisions at Bevatron-Bevalac energies (few GeV/nucleon) is given to test to what extent such collisions can be compared to nucleon-nucleon studies performed at NAL and ISR energies. Data are examined for such phenomena as limiting fragmentation, scaling, and factorization of cross-sections. A brief discussion of experiments--either in progress or about to start, which bear on the question of testing high energy interaction models--is included.

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INTRODUCTION

With the successful acceleration of deuterons and heavier nuclei in the Bevatron in late 1971, a substantial program of research with high-energy heavy ions began. This program has been multidisciplinary in nature, covering the areas of particle, nuclear and astrophysics. We will be concerned with some of the possible contributions to particle physics of the program.

Chew⁽¹⁾ has suggested that studies of nucleus-nucleus collisions at energies of a few GeV/nucleon should yield information which would be useful for testing high energy models. These models have previously been restricted to particles with baryon number 0 or 1. If this suggestion is correct, then high-energy heavy ions represents a new tool for studying such models. Two points should be kept in mind when considering Chew's suggestion—one concerning the energy scale in the interaction, and the other the "constituent" nature of the interacting systems. When testing high-energy models, one should be in the asymptotic energy region. This region can be defined by the energy of the system compared to the average energy of its low-lying resonances. For nuclei at a few GeV/nucleon, one is well above the characteristic level spacings which are ~ 10 -100 MeV. However, with hadrons, one must be at much higher energies since the characteristic level spacings are of the order of a few GeV or so. Secondly, data on hadron-hadron collisions at higher energies suggest a detailed constituent nature to hadrons. These are the so-called "quarks" or "partons" of various models. Nuclei clearly exhibit a "constituent" nature, since they are composed of nucleons. By reviewing the existing data we attempt to see if there are any similarities between nucleus-nucleus collisions at a few GeV/nucleon and high-energy hadron-hadron collisions.⁽²⁾

NUCLEUS-NUCLEUS COLLISIONS AT A FEW GEV/NUCLEON

Before turning to the data, it would be useful to list the present experimental parameters which are available at the Bevatron/Bevalac facility. The Bevalac is a marriage of the SuperHILAC at Berkeley to the Bevatron. The SuperHILAC operates as the injector of heavy ions, which are then accelerated in the Bevatron. Table I lists the ions which are or will be available along with expected beam intensities.

Table I Types and Fluxes of Heavy Ions at Bevalac Facility

<u>ION*</u>	<u>PARTICLES/PULSE</u>
^1H	5×10^{12}
^2H	2×10^{11}
^3He	10^{11}
^4He	2×10^{10}
^6Li	3×10^{10}
^{10}B	3×10^{10}
^{12}C	6×10^{10}
^{14}N	3×10^{10}
^{16}O	3×10^{10}
^{20}Ne	10^{10}
^{40}Ar	5×10^8
^{56}Fe	5×10^5
^{84}Kr	5×10^4

*All ions are fully stripped.

The energies of the ions can be continuously varied from 0.2-2.5 GeV/nucleon (kinetic energy/nucleon). Operation of the Bevatron/Bevalac combination was started in August, 1974. Previously, the Bevatron had used its own injector as the ion source, but with limited beam intensities of ions with $A > 4$.

We first examine to what extent such concepts as fragmentation, scaling, factorization, etc., hold for nucleus-nucleus collisions at energies of a few GeV/nucleon. First the question of fragmentation. Do well-defined fragmentation regions exist where the process can be separated into either projectile fragmentation, target fragmentation, or both? At low energies (10's of MeV) one could not expect well-defined fragmentation regions to exist. At higher energies, these regions could be separated by some reasonably large rapidity interval, as illustrated in Figure 1. The first clear indication of a well-defined fragmentation region was observed by Heckman et al.⁽³⁾ in single particle inclusive studies at 0° with incident ^{14}N and ^{16}O beams. Data from their study of $^{16}\text{O} + \text{Be} \rightarrow {}^A\text{C} + \text{X}$, where ${}^A\text{C}$ is a carbon isotope, is shown in Figure 2. The incident energy was 2.1 GeV/n. Figure 2a shows the momentum distribution in the laboratory of all observed carbon isotopes. When these distributions are transformed to the projectile rest-frame, a majority of the distributions are observed to peak near zero momentum. An example of this is shown in Figure 2b for ^{13}C fragments. This suggests that in the fragmentation process, fragments of the projectile are emitted with the same velocity as the projectile, and are well separated from other processes. A study⁽⁴⁾ of the fragmentation of ${}^4\text{He}$ into p, d, ${}^3\text{H}$, and ${}^3\text{He}$ at a fixed laboratory angle of 2.5° also supports such a conclusion. In Figure 3a is shown the laboratory momentum distribution of these fragmentation products. When these data are plotted versus the fragment rapidity, fragmentation peaks are seen centered on the rapidity of the incident projectile as shown in Figure 3b. The rapidity of the target is zero; so there is a clear separation between target and projectile fragmentation regions, at these energies.

If limiting fragmentation is a valid concept for heavy-ion fragmentation processes it is expected that the fragmentation will be independent of the energy and of the target employed. The fact that the shapes of the momentum spectra observed in the fragmentation of ^{14}N and ^{16}O beams are independent of the target material supports this conclusion.⁽³⁾

In Figure 4a and 4b are shown data from Reference 4 on the processes, $d + C \rightarrow p + x$ and $\alpha + C \rightarrow p + x$, at two different incident energies. The data are plotted in the projectile rest-frame. Fragmentation peaks are clearly evident and are consistent with being energy independent over the range 1-2 GeV/n. This same conclusion holds when other targets are used, so that limiting fragmentation appears to apply in these high energy projectile fragmentation processes. Additional insight into the fragmentation process can be obtained from a knowledge of the dependence on target material. Data of Reference 4 for the fragmentation of incident deuterons and alphas into protons has been fit to the form, $\sigma \sim A^n$, where A is the mass (in amu) of the target used (Be, C, Cu, Pb). The value of the coefficient n obtained from the fit as a function of the observed proton momentum is shown in Figure 5 for 2.1 GeV/n deuteron and alpha beams. For momenta in the fragmentation region ($P_{lab} \geq 2 \text{ GeV/c}$) the cross-section varies like $A^{1/3}$, suggesting that the fragmentation process is peripheral.⁽⁵⁾ As the proton momentum is reduced the A-dependence grows sharply, indicating that other processes besides simple projectile fragmentation are contributing to the production of protons.

We now consider the results on pion production.⁽⁴⁾ In Figure 6a the invariant cross section for negative pion production by protons with energies between 1.05 and 4.2 GeV is plotted versus the scaling parameter, $x' = \frac{k_{\perp}^*}{(k_{\perp}^*)_{\max}}$. All of the data points are seen to lie on a universal curve, suggesting that negative inclusive pion spectra scale even at 1 GeV; a somewhat unexpected result. The production of negative pions by 1.05 and 2.1 GeV/n deuteron and alpha beams shown in Figures 6b and 6c also exhibit this premature scaling feature. As in the case of projectile fragmentation, the shapes of the pion spectra are found to be independent of the target and consistent with an $A^{1/3}$ dependence for pion momenta $> 1 \text{ GeV/c}$.⁽⁴⁾ as shown in Figure 7 for 2.1 GeV/nucleon alphas.

An added similarity between high-energy nucleon-nucleon collisions and heavy-ion collisions involving leading particle effects is worth noting. It has been known for a long time that the process $pp \rightarrow p + x$ at high energies is characterized by a large quasi-elastic peak which is related to the diffractive production of high mass states.⁽⁶⁾ This process has

its analog in nucleus-nucleus collisions as shown in Figure 8 for deuteron or alpha beams. In this example, the analog of the high mass states of the proton are the highly excited levels of the nuclear target. In the case shown in Figure 8, A^* represents either the particle stable or particle unstable states of the nuclear target. Both the alpha particle distribution shown in Figure 3a and the deuteron distribution seen in Figure 9 bears a strong resemblance to the high energy inclusive proton spectra.⁽⁶⁾ It is interesting to speculate whether one can apply triple-Regge theory to such inclusive distributions in nucleus-nucleus collisions at Bevalac energies, since the data of Reference 4 indicates that the leading particle spectra are similar in shape to those observed in high energy pp collisions. An experiment⁽⁷⁾ to test whether Regge phenomenology is applicable to nucleus-nucleus collisions at Bevalac energies is presently being undertaken.

EXPERIMENTS IN PROGRESS AND FUTURE POSSIBILITIES

An experiment⁽⁸⁾ to measure nucleus-nucleus total cross sections at Bevalac energies has been completed and the data are presently being analyzed. The experiment has measured total cross-sections for the following systems:

pp	pd	pa	pc
	dd	da	da
		aa	ac
			cc

Data from this experiment can be used to test various multiple scattering theories for the scattering of a composite system by a composite system. Prior to this experiment only the d-d system had been studied to test such models. Data from this experiment can also be used to test if nucleus-nucleus collisions obey the factorization relation, $\sigma_{AA} \sigma_{BB} = (\sigma_{AB})^2$. Using a variety of models, several theorists⁽⁹⁾ have recently been concerned with this problem. Although no experiments on wide angle elastic scattering of composite systems are presently proposed, such experiments would provide a vigorous testing ground for high energy multiple scattering theories.

Nuclei with $I = 0$ will play an important role in experiments to investigate the $I = 0$ meson spectrum and the $I = \frac{1}{2}$ baryon spectrum. Experiments⁽¹⁰⁾ like:

guarantee that the MM spectrum is in an $I = 0$ state. For example, one could look for ω -production and extract the $\omega + 2\pi$ branching ratio without ρ -interference. Studies of the $I = \frac{1}{2}$ N^* spectrum could be made by investigating reactions like:

where MM is guaranteed to be in the $I = \frac{1}{2}$ state. If high statistics are obtained, then branching ratios of N^* 's to $N\pi$, $N\pi\pi$, ΛK and other final states could be extracted. Although one could use carbon beams for such studies, deuterons and alphas are preferable since they have no particle stable excited states and are relatively easy to detect in the final state.

Because nuclei are stable, high energy nuclei might provide a valuable tool for testing high-energy high-spin theories.⁽¹¹⁾ Studying the scattering of systems with high spin is difficult if one tries to use N^* 's due to their short lifetimes. Heavy nuclei can also be used to test Q.E.D. for systems with very large Z .⁽¹¹⁾

A majority of the experiments that have been discussed have been of an inclusive nature. An experimental program utilizing heavy ions and the LBL streamer chamber is getting under way.⁽¹²⁾ The streamer chamber will offer the advantages of $\sim 4\pi$ acceptance combined with trigger capability. Both inclusive and exclusive studies can be performed. Such things as pion multiplicities, projectile fragmentation, and correlations of particles in the projectile fragmentation process can be studied. A preliminary run with a 0.87 GeV/n carbon beam was successful in demonstrating that the streamer chamber techniques will be a powerful tool for investigating nucleus-nucleus collisions.

CONCLUSIONS

Existing data on nucleus-nucleus collisions at 1-2 GeV/nucleon are found to exhibit many features in common with high-energy nucleon-nucleon collisions. Further experimental studies are under way to see if the similarities have a common foundation. If they do, then high-energy heavy ions offer an additional way to study high-energy models, and serve as a bridge that can connect ideas which have been used in nuclear physics and particle physics.

It should be emphasized that the use of high-energy heavy ions to study high-energy interaction models represents a small part of the research program with heavy ions at the Bevalac. This program covers the areas of nuclear, particle, and astro-physics as well as biology and medicine.

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^4He or ^{12}C . An experiment study $dd + ^4\text{He} + MM$ has recently been performed at the Saturne machine at Saclay by the Goldzahl group (private communication).

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FIGURE CAPTIONS

- Fig. 1. Examples of projectile and target fragmentation at low and higher energies. A refers to projectile and B to target.
- Fig. 2. Data from Ref. 3 for the reaction $^{16}\text{O} + \text{Be} \rightarrow ^A\text{C} + \text{X}$. (a) Momentum spectrum for carbon isotopes produced at 0° by fragmentation of 2.1 GeV/n ^{16}O beams; (b) Parallel and transverse momentum distributions for ^{13}C fragments in projectile rest frame.
- Fig. 3. Fragmentation of 1.05 GeV/n ^4He at a laboratory angle of 2.5° for data of Ref. 4. (a) Laboratory momentum distribution of fragments. (b) Lorentz invariant cross-section versus rapidity of fragments. Rapidity of beam projectile ~ 1.4 .
- Fig. 4. Data from Ref. 4 Lorentz invariant cross-section for fragmentation into a proton for a) deuteron beams, and b) alpha beams versus the momentum in projectile rest frame. Beam energies are 1.05 and 2.1 GeV/n.
- Fig. 5. Dependence on the deuteron and alpha beam fragmentation to protons at 2.1 GeV/n. The data for the various targets was fit (least squares) to the form; $\sigma \propto A^n$, A is mass of target.
- Fig. 6. Invariant cross section for negative pion production from Be target versus scaling variable x , (a) incident protons, 1.05-4.2 GeV; (b) incident deuterons, and (c) incident alphas at 1.05 and 2.1 GeV/n. All measurements at a fixed lab angle of 2.5° .
- Fig. 7. Dependence of the pion production cross section on target material for 2.1 GeV/n incident alphas. The data for the various targets was fit (least squares) to the form; $\sigma \propto A^n$, A is a mass of target. The coefficient n is plotted versus momentum of the produced pion.
- Fig. 8. Diffractive excitation of the nuclear target by incident d or α beams.
- Fig. 9. Data of Ref. 4 showing the quasi-elastic region for the reaction $\text{d} + \text{Be} \rightarrow \text{d} + \text{x}$ at 1.05 GeV/n.

Fig. 1

Fig. 2a

XBL 736-777

Fig. 2b

XBL 7310-4265

Fig. 3a

Fig. 3b

XBL7310-4266

Fig. 4a

Fig. 4b

Fig. 5

Fig. 6a

Fig. 6b

XBL 7310-4263

Fig. 6c

Fig. 7

XBL 748-3900

Fig. 8

XBL 7310-4267

Fig. 9