PARTICLE PRODUCTION IN HIGH ENERGY NUCLEUS-NUCLEUS EXPERIMENTS AT BERKELEY

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ABSTRACT

A review of high energy nucleus-nucleus experiments performed at the Berkeley Bevalac is presented. Earlier results on projectile and target fragmentation and pion production are briefly summarized. More recent results on Coulomb effects in projectile fragmentation, heavy ion total cross-sections, γ-ray production, and charged particle multiplicities are presented. Also, recent experiments which may shed light on phenomena arising from the central collision of two energetic nuclei, including recent evidence for and against the observation of nuclear shock waves, are reviewed.

INTRODUCTION

A vigorous research program with relativistic nuclear beams has been underway at Berkeley for the last few years. Initially, these beams were provided by the Bevatron's own 20 MeV linac injector. Running in this mode, the Bevatron could supply reasonably intense beams of protons, deuterons, and alphas; as well as much less intense beams of carbon, nitrogen, and oxygen ions. With these beams, a program of nuclear science and biology and medicine research began.

In 1974, the Bevalac Facility came into existence. The Bevalac is a marriage of the SuperHILAC and Bevatron. The SuperHILAC acts as an injector of 8.5 MeV/nucleon heavy ions into the Bevatron, where they are then accelerated and extracted into the experimental hall. Final energy of the ions can be continuously varied from 0.2-2.5 GeV/nucleon (kinetic energy/nucleon). Operating in this mode, the Bevalac can provide much more intense beams of light ions (up to 10^{10}/pulse for carbon through neon), and also much heavier beams (at present Fe is the heaviest at intensities of few 10^4/pulse). Beams are time shared between the SuperHILAC and the Bevatron, so that the SuperHILAC can run its own low energy nuclear science program at the same time. Since there are two independent ion sources at the SuperHILAC, the normal running conditions are that two different ions are in use; one for the SuperHILAC (e.g., Xe) and one for the Bevalac (e.g., Ne).

At the Trieste Meeting of 1974, Herb Steiner reviewed the relativistic heavy ion program at Berkeley.[1] Areas covered included projectile and target fragmentation, pion production, and a brief review of some experiments then in progress. My intention is to first briefly review some of the experimental high lights presented in Steiner's talk. I will use this to serve as a background for the remainder of my talk, which will cover new results which have emerged since late 1974 in the area of high energy heavy ion interactions including the exciting possibility of forming larger than normal nuclear densities. Speculations concerning the possibility of nuclear shock waves,[2] pion condensates,[2,3] or abnormal nuclear matter[3,4] have been prominent over the period of the last 2 or 3 years, and are the basis for a large number of the experiments that are presently under way at the Bevalac.

REVIEW OF EARLIER NUCLEUS-NUCLEUS RESULTS

I now want to briefly review some of the highlights (including motivation and results) of the experimental program with nuclei that Herb Steiner reported on at the 1974 Trieste Meeting.[1] With this as a background, I will then move on to a discussion of more recent experimental results.

One of the first processes to be studied with nuclear beams was the work on projectile fragmentation by the Heckman/Greiner group.[5] This process can be characterized as one in which very little energy and momentum is transferred to the incident projectile. As a consequence, the projectile fragments are emitted fast and forward in the laboratory frame. Figure 1 shows an example of such a fragmentation. In this streamer chamber picture,[6] we see the

Fig. 1. Fragmentation of 0.87 GeV/nucleon ^{12}C beam on lucite target into six charged particles. *Picture taken in LBL streamer chamber by the U. C. Riverside/LBL* collaboration.[6]

breakup of an 0.87 GeV/nucleon ^{12}C on a lucite target placed in the chamber. The ^{12}C breaks up into six outgoing charged particles; each making a small angle with respect to the incident projectile. Their interest in studying projectile fragmentation was the following:

(1) Fragmentation cross sections are needed to understand the propagation of cosmic rays through space.

(2) Measurements of single-particle momentum spectra of projectile fragments might serve as a means of measuring the internal momentum distributions of particles inside nuclei.

(3) Test whether the high energy concepts of factorization and limiting fragmentation might apply to the fragmentation process at Bevalac energies.

These experiments[5] measured the single-particle momentum spectra at $\theta_{LAB} \approx 0^\circ$ of 1.05 and 2.1 GeV/nucleon incident C, N, and O projectiles fragmenting on a varity of nuclear targets. The following can be summarized from their studies:

(1) For the majority of fragments, the single-particle momentum distributions are Gaussian in shape and are peaked near zero momentum in the projectile rest frame. An example of this is shown in Fig. 2. These distributions can be parameterized in the projectile rest frame as:

$$\frac{d^3\sigma}{dp^3} = ce^{-p_\perp^2/2\sigma_\perp^2}\, e^{-((p_\parallel - \langle p_\parallel \rangle)^2/2\sigma_\parallel^2)}$$

where $p_\perp$ and $p_\parallel$ are the transverse and longitudinal momentum of the fragment, $\langle p_\parallel \rangle$ is the value of the off-set from zero momentum

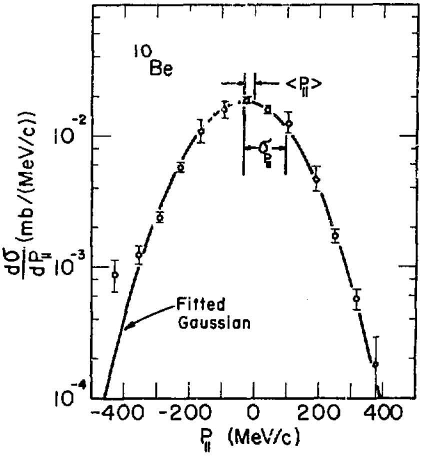

Fig. 2. Example of the fragmentation process $^{12}C + Be \rightarrow {}^{10}Be + X$ at 2.1 GeV/nucleon. Data from Heckman/Greiner group.[5] Cross-section vs longitudinal momentum in projectile rest frame.

(see Fig. 2), and $\sigma_\perp$ and $\sigma_\parallel$ are FWHM of the transverse and longitudinal momentum distributions. Within their estimated errors of $\pm 10\%$, they find that $\sigma_\perp = \sigma_\parallel$.

(2) They find that the dependence of the Gaussian momentum distributions on projectile and fragment masses is of the form:

$$\sigma_\parallel^2 \propto \frac{F(B - F)}{B^2}$$

where F and B are respectively, the masses of the fragment and projectile. This parabolic dependence has been predicted by a number of models, and is essentially a consequence of the conservation of energy and momentum.[7]

(3) Fragmentation cross sections are found to factor into target and projectile related parts. Writing the reaction as, A + B → C + X, factorization can be expressed as:

$$\sigma_{AB}^{C} = \gamma_A^C \gamma_B$$

where γ_A^C depends only on the projectile and the detected fragment, and γ_B depends only on the target material. They find that $\gamma_B \propto B^{1/4}$, suggestive of a peripheral interaction. It is also possible to parameterize the cross section as $\gamma_B \propto (A^{1/3} + B^{1/3} - \varepsilon)$, where ε plays the role of an overlap parameter. Their data do not distinguish between the two parameterizations.

A number of models have been constructed which reproduce some of the regularities that have been observed in the projectile fragmentation process. I refer you to a paper by A. Goldhaber[7] which reviews these early attempts. Most recently, Hüfner and collaborators[8] have extended an abrasion-ablation[9] model to explain these data. In this model, the fragmentation takes place in two stages; in the first, the abrasion stage, the overlapping nuclear matter is sheared away from the projectile and target. The remaining pre-fragment, which recoils with a momentum proportional to the Fermi momentum, is left in the excited state and subsequently decays (ablation stage). Glauber theory is used to describe the abrasion stage; while they assume thermalization of the pre-fragment and compound nucleus decay for the ablation stage. They obtain reasonable agreement with the data. This approach appears promising, but will probably require more refinement.

Light-ion fragmentation and pion production have been investigated by Papp et al.[10,11] They measured the single-particle inclusive spectra for:

$$\begin{pmatrix} p \\ d \\ \alpha \\ C \end{pmatrix} + A \rightarrow \begin{pmatrix} \pi^{\pm} \\ p \\ d \\ {}^3H \\ {}^3He \\ \alpha \end{pmatrix} + X \ , \quad \theta_{LAB} = 2.5°$$

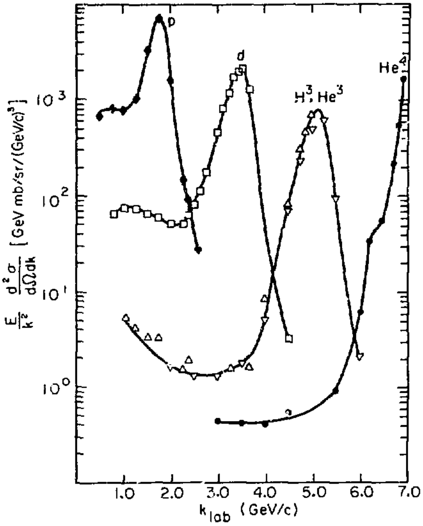

Fig. 3. Data of Ref. 10 for the fragmentation of 1.05 GeV/nucleon alphas by a carbon target. Individual fragments, detected at $\theta_{LAB} = 2.5^{\circ}$, are indicated.

Protons of 1.05-4.2 GeV, deuterons and alphas at 1.05 and 2.1 GeV/nucleon, and 1.05 GeV/nucleon carbon nuclei were used to *study production* from Be, C, Cu, and Pb targets. Figure 3 shows the invariant cross section

$$E/k^2\left(\frac{d^2\sigma}{d\Omega dk}\right)$$

resulting from the collision of 1.05 GeV/nucleon alphas on a carbon target plotted against the momentum of the fragment produced at 2.5°. The fragmentation of the incident alpha into its p, d, ^{3}H and ^{3}He components is clearly evident by the peaks in the individual momentum spectra. Notice that for fast, forward fragments, projectile fragmentation dominates all other processes. The position of the peaks correspond to approximately zero momentum in the projectile rest frame. A result in agreement with the findings of the Heckman/Greiner group for the fragmentation of heavier ions. To obtain more information on the fragmentation process, these data were studied for their dependence on target material by assuming the cross sections vary as: $\sigma \propto A^n$, where A is the mass of the target. Figure 4 shows a plot of the coefficient n vs momentum for the reactions, $dA \to p + x$ and $\alpha A \to p + x$ at 2.1 GeV/nucleon. In the projectile fragmentation region, the cross section varies as $A^{1/3}$, suggestive of a peripheral interaction. At lower momenta, the cross section rises rapidly, indicating that other processes are starting to contribute to the production of particles. Bertocchi and collaborators[14] have used a Glauber model for the reaction, $d + A \to p + x$, at 1.05 and 2.1 GeV/nucleon. They are able to explain the width of the proton spectrum (see proton peak in Fig. 3) as resulting from the relativistic dilation effect of the proton's spectrum when transformed from the deuteron rest frame to the laboratory frame where the protons are detected.

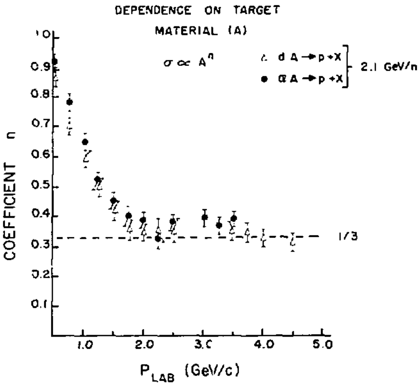

Fig. 4. Dependence of cross section on A. Reference 10 has assumed a form: $\sigma \propto A^n$, where A = target mass.

In experiments on high energy pion production, Papp et al.[11] were interested in determining the extend to which very energetic pions, that is, pions with energies considerably larger than those which result from simple nucleon-nucleon collisions, are produced in the collisions of deuterons and alphas with other nuclei. Can such high energy pions be explained in terms of nucleon-nucleon processes in which Fermi motion is included in both target and projectile, or are more complicated processes required? In addition, such data can be used to test whether scaling holds in these collisions.

A remarkable feature of pion production by high energy protons, deuterons, and alpha particles appears when the invariant cross section is plotted against the scaling parameter,

$$x' = \frac{(k_{\parallel}^{*})}{(k_{\parallel}^{*})_{max}}$$

as shown in Fig. 5. For production by protons (Fig. 5a), all the data (1.05-4.2 GeV protons) are seen to lie on a universal curve, suggesting that the negative pion spectra scale even at 1 GeV, a somewhat unexpected result. High energy data points from the CERN PS also fall on this same curve. A similar scaling is observed for the 1.05 and 2.1 GeV/nucleon deuteron and alpha data (Fig. 5b).

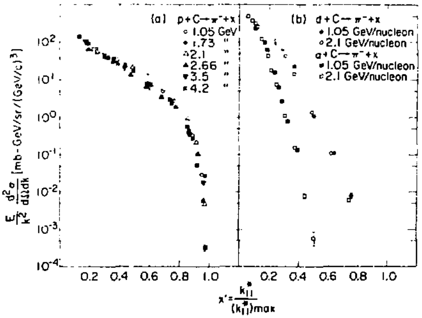

Fig. 5. Invariant cross section (Ref. 11) for negative pion production at 2.5° (Lab) (a) incident protons (1.05-4.2 GeV), (b) incident deuterons and alphas (1.05 and 2.1 GeV/nucleon).

Negative pion production cross sections[11] for 2.1 GeV/nucleon protons, deuterons, and alphas incident on a carbon target are shown in Fig. 6.

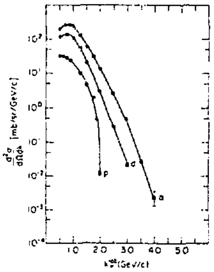

Fig. 6. Laboratory cross section ($d^2\sigma/d\Omega dk$) for π^- production (Ref. 11) at 2.5° (Lab) for 2.1 GeV/nucleon p, d, α on carbon target.

At the same incident kinetic energy/nucleon, deuterons and alphas clearly produce pions with higher momenta than do protons. The question remains, is this caused by the interaction of several nucleons inside the incident projectile acting in a cooperative fashion, or is it just a single nucleon-nucleus collision with the inclusion of Fermi motion in both target and projectile? Figure 7a shows the results of a calculation by the Berkeley group[11] based on a model in which all pions are produced in individual nucleon-nucleus collisions with Fermi motion included. The predictions are compared with the 1.05 and 2.1 GeV/nucleon deuteron data taken with a carbon target. The general trend of the measured cross-sections for fast pions is reproduced quite well. These results disagree with the conclusions of the Dubna group[13] who claim to be unable to fit their data with a similar model.[13,14] It should be pointed out that for the case of production by deuterons, one can not

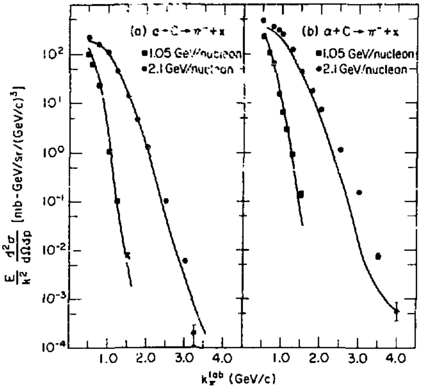

Fig. 7. Invariant cross section for negative-pion production at 2.5° (Lab) at 1.05 and 2.1 GeV/nucleon (a) deuteron and (b) alpha beams. The solid line represents the prediction of model described in Ref. 11.

distinguish between a Fermi motion model (Berkeley group[11]) and a model with collective effects (Dubna group[13]), since they amount to the same thing. That is, for the deuteron case, large Fermi momentum components necessarily imply that the two nucleons are spatially close together and are, therefore, correlated. This suggests that pion production by much heavier projectiles ($\gtrsim$ carbon) could be a better choice for comparing the two mechanisms.

The model used by the Berkeley group has also been applied to negative pion production by alpha particles. The comparison between the model and the data is shown in Fig. 7b. Although the general trend of the data is followed, quantitatively the agreement is poor. This could be due to a breakdown of the model, or to a poor choice for the single-nucleon momentum distribution, which for the alpha particle is not well known. Indeed, one of the interesting possibilities associated with pion production will be the possibility of extracting information concerning nucleon momentum distributions, and in particular, the high momentum components of these distributions. Further systematic experiments with heavier projectiles are required to see if the Berkeley model will hold up.

Finally, the Berkeley group has investigated the dependence of pion production on target material, finding that it typically varies as $A^{1/3}$ for $k_\pi \gtrsim 1$ GeV/c suggesting a peripheral production mechanism for the high energy pions. For lower momentum pions ($\lesssim 1$ GeV/c), the dependence is more produced, suggesting that slow pions are produced in more central collisions. These effects are observed in both the 1.05 and 2.1 GeV/nucleon deuteron and alpha-induced pion production.

Up to now I have been primarily reviewing fast particle production at forward angles. These particles to a large extend can be associated with the projectile. Measurements of target related fragments have been undertaken. Of particular interest in these experiments is the question of whether energetic nuclei can deposit more energy in a target nucleus, than say a pion or proton. The Poskanzer group[15] has measured the energy and angular distributions of fragments (He to B) from a uranium target irradiated by 4.9 GeV protons and 2.1 GeV/nucleon deuteron and alpha beams. Relative cross sections for the production of ^{4}He and ^{7}Li fragments at 90° in the laboratory are plotted against the recoil kinetic energy in Fig. 8. Also included in Fig. 8 are more recent data[16] from 2.1 GeV/nucleon ^{12}C and ^{20}Ne runs. From this representation of the data we can see that incident deuterons do not appear to produce significantly more fragments than do high energy protons. However, in the interaction of α, C, and Ne with uranium there is definite indication of larger fragment yields, suggesting a larger deposition energy. I will return to this significant point a little later in the discussion on central collisions.

RECENT RESULTS ON PERIPHERAL COLLISIONS

Now I would like to move on to more recent results involving nucleus-nucleus peripheral

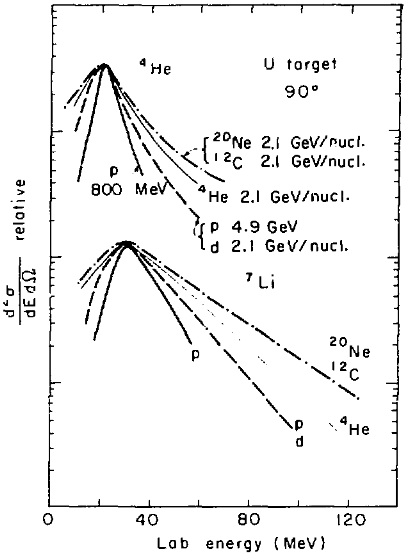

Fig. 8. Relative cross sections (Refs. 15 and 16) for the production of ^{4}He and ^{7}Li fragments at 90° from a uranium target bombarded by various energy p, d, α, C, and Ne beams.

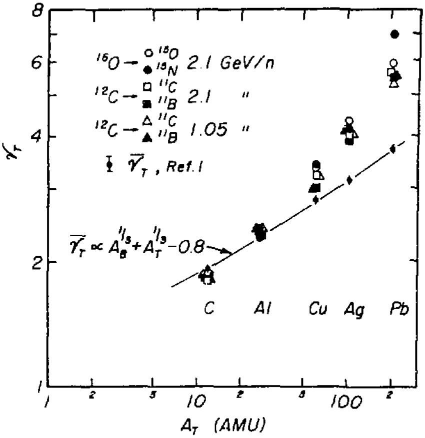

Fig. 9. Target factor γ_T vs target Mass. Data are for single nucleon removal reactions by ^{12}C and ^{16}O beams at 1.05 and 2.1 GeV/nucleon.

interactions; including, projectile fragmentation studies, heavy ion total cross sections, and γ-ray production.

Recent analysis[17] of projectile fragmentation processes which involve the removal of a single nucleon (e.g., $^{16}O \rightarrow {}^{15}O + n$ or $^{15}N + p$) has shown an interesting deviation in dependence on target mass when compared to the target dependence for processes which involve the removal of several nucleons from the projectile. Figure 9 shows the target factor, γ_T, plotted against the mass of the target. Data shown are for single nucleon removal reactions. The solid curve (labelled $\bar{\gamma}_T$) represents the behavior for all other measured fragmentation processes. The single nucleon removal data is seen to follow this trend for light targets, but shows strong deviations for heavier targets. These deviations were found to be proportional to Z^2, suggesting that Coulomb dissociation plays a major role. A simple model which employs the Weizsacker-Williams approximation has been used to explain these data. In this model, the cross section for single nucleon removal is given by:

$$\sigma_{WW} = \int \sigma(\omega)\; N(\omega)\; d\omega$$

where σ_{WW} is the cross section of interest, $\sigma(\omega)$ is the photo-nuclear cross section as a function of photon frequency ω, and $N(\omega)$ is the density of photons obtained using Weizsacker-Williams techniques. Figure 10 shows the results of such a calculation compared with the data. The data and model are in excellent agreement; for certain processes it is clear that Coulomb forces play a major role in projectile fragmentation.

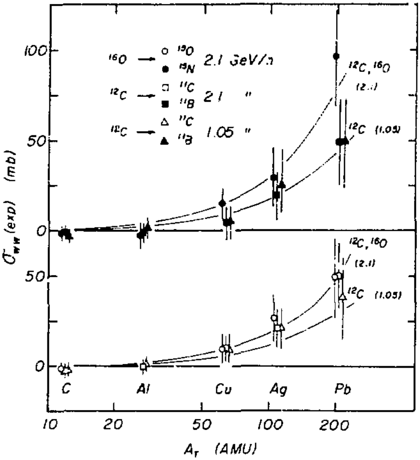

Fig. 10. Experimental data (Ref. 17) for single nucleon removal reactions compared to results of model calculation using Coulomb dissociation.

A systematic measurement of nucleus-nucleus total cross sections for all possible target (p,d,α,C), projectile (p,d,α,C) combinations at 0.87 and 2.1 GeV/nucleon has been performed.[18] Glauber multiple scattering theory has been extended to nucleus-nucleus collisions.[19] The theory is essentially geometrical and predicts that

$$\sigma_T \propto \left(A_{\rm tgt}^{1/3} + A_{\rm proj}^{1/3}\right)^2 .$$

Gribov[20] has pointed out that if one naively applies Regge factorization to nucleus-nucleus collisions it leads to a very different A-dependence for σ_T than expected from geometrical considerations. Assuming factorization and Pomeron dominance of the elastic scattering amplitudes, one can show that this reduces to: $\sigma_T(AA) \propto A^{4/3}$. Thus, factorization predicts $A^{4/3}$, while a Glauber approach would predict $A^{2/3}$, quite different and easily distinguishable results.

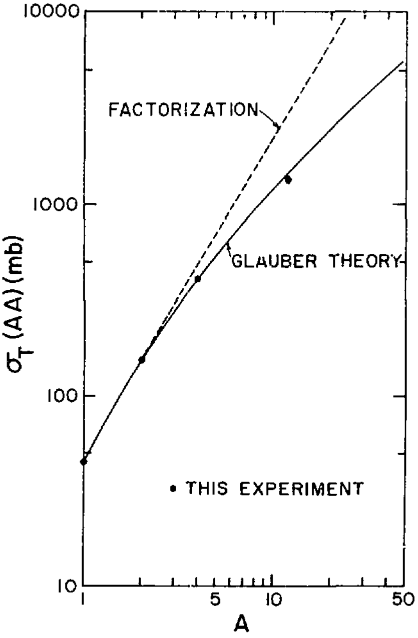

Fig. 11. Measured heavy ion total cross sections (pp, dd, $\alpha\alpha$, CC) compared with predictions of factorization and Glauber model.

Figure 11 shows the results of these total cross-section measurements at 2.1 GeV/nucleon. The solid and dashed curves are the predictions of Glauber theory and the factorization relation, respectively. The data is in excellent agreement with the Glauber prediction for all data points, except the CC point which lies slightly below the Glauber theory prediction. The fact that the factorization prediction is not satisfied could be anticipated, since it is only taken to be valid at energies much larger than those available in this experiment.

The TOSABE group[21] has been measuring γ-ray production. By looking for γ-rays from known nuclear levels they hope to select peripheral interactions; in particular, they expect to obtain information on the transferred angular momentum in these collisions. By identifying the residual nucleus, additional information on reaction mechanisms (e.g., nucleon or alpha knock-out) will substantially add to an understanding of the dynamics of peripheral nucleus-nucleus collisions. Identification of individual lines in these experiments are difficult due to the large backgrounds present. Experiments using carbon projectiles at 250 MeV/nucleon and 1.05 GeV/nucleon on various targets (^{12}C, ^{19}F, Sr, ^{207}Pb) have been done. Figure 12 shows a sample spectrum from a ^{207}Pb target. Note that the cross sections for known γ-rays are typically in the 10-100 mb range. There are earlier indications that high spin-states of the target are excited in these collisions.[21] This is not observed in experiments at much lower energies (~10 MeV/nucleon).

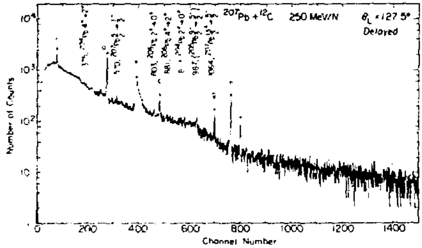

Fig. 12. Example of γ-ray spectrum produced at 127.5° by 250 MeV/n carbon ions on ^{207}Pb. Known lines are indicated (small letters refer to known lines from known material near target area).

SEARCH FOR NEW PHENOMENA RESULTING FROM THE CENTRAL COLLISION OF RELATIVISTIC NUCLEI

As indicated earlier in this talk, evidence[15,16] exists that high energy nuclei provide a more effective tool for bringing in and depositing large amounts of energy and momentum in a target nucleus, than does a pion or nucleon. Up to this point, most of the experiments that have been described have involved relatively small amounts of energy and momentum being transferred. Where would we expect to find processes that involve large energy-momentum depositions, and what will their experimental signature be? Certainly, when two nuclei collide in a central fashion, the probability for interaction is increased, and, therefore, one expects that these events will have the best chance for depositing large amounts of energy and momentum. For a central collision, if the two nuclei are not transparent to each other, and provided there is a large transfer of energy and momentum, one would expect to see a large number of particles liberated. An illustration of this is seen in Fig. 13,[6] which shows the collision of a 1.8 GeV/nucleon Ar nucleus with a lead-oxide target located inside the LBL streamer chamber. In this catastrophic event, a large number of positive and negative charged particles were produced, with no large mass remnants of the projectile appearing from the interaction.

There has recently been increasing theoretical interest in heavy ion collisions at relativistic energies. The most exciting speculations have concerned the possibility of observing new phenomena associated with the central collisions of these energetic nuclei. These include abnormal nuclei,[4] highly excited nuclear matter,[22] nuclear shock waves,[2] and pion condensates.[3] These speculations have been greeted by intense experimental activity and I now want to turn to some of these experiments.

Historically, the abnormal states suggested by Lee and Wick,[4] were the first to receive experimental attention; but with no positive results.[23] At this same time, predictions of nuclear shock waves carying large transverse energy and momentum were coming into prominence.[2] It was suggested that shock waves might be produced in central collisions when the projectile velocity exceeds the nuclear sound velocity, $v_o \approx 0.2\ c$. If such a disturbance were produced and propagated through the nuclear medium, upon impacting the surface it would eject particles. These particles would be numerous and have relatively large energies ($\gtrsim$10-20 MeV/nucleon). Some models[24,25]

Fig. 13. 1.8 GeV/nucleon ^{40}Ar projectile interacting with a Pb_3O_4 target inside LBL streamer chamber. Positive particles bend down in magnetic field of chamber, and negative tracks bend up.

predicted that emission would occur in a narrow band of angles which would move backward as the projectile energy was increased. A hydrodynamic model suggested that the angular range for emission would be larger.[26] This suggests that a possible key to the detection of nuclear shock waves, would be the presence of peaks in the angular distribution.

The Frankfurt group[24] using Ag-Cl detectors exposed to carbon and oxygen beams observed peaks in the angular distribution [$N(\theta) = d\sigma/d\theta$] of fragments at several energies. To select central collisions, they choose only so-called "star events;" those exhibiting a large number of prongs. In this experiment, no particle identification was made. However, their detectors are sensitive to protons less than 28 MeV ($\beta \approx 0.24$) and He nuclei less than 200 MeV/nucleon ($\beta \approx 0.57$). They conclude that the particles in their angular distributions, are dominately protons and He nuclei. Figure 14 shows angular distributions, for "star" events, from ^{16}O and ^{12}C bombardment of their detector. Note that they plot $d\sigma/d\theta$ rather than $d\sigma/d\Omega$ [$d\sigma/d\theta = 2\pi\sin\theta(d\sigma/d\Omega)$]. In each of the angular distributions a relatively narrow peak ($\approx$20–30°) is present, which shifts to backward angles with increasing projectile energy. The solid curve is their estimate of particles evaporated from the target. Using these[24] and later data,[27] they conclude that they have positive evidence for nuclear shock waves.

In an effort to study the possibility of shock wave emission of nuclear fragments with higher statistics, Poskanzer et al.[16] in a single-particle inclusive counter experiment have measured the energy and angular distribution of ^{3}He and ^{4}He fragments from a silver and uranium target bombarded by protons, alphas, and ^{16}O ions. Figure 15 shows their angular distribution ($d\sigma/d\Omega$) for ^{3}He and ^{4}He fragments with energy cuts to duplicate as nearly as

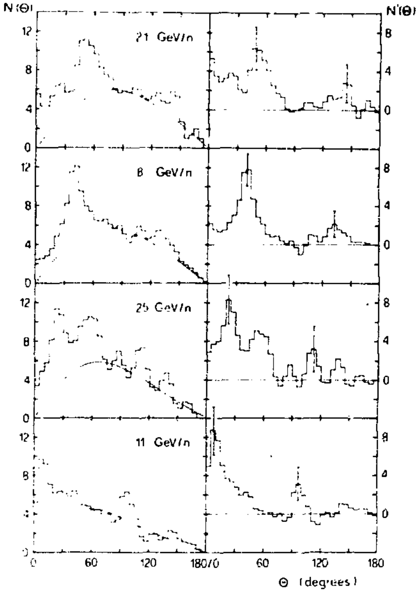

Fig. 14. Data of Ref. 24. Left-hand column contains their angular distributions requiring a large multiplicity of prongs. Right-hand column contains angular distribution after background subtraction. 2.1 and 0.87 GeV/n data are for ^{16}O projectile, 0.25 and 0.11 GeV/n data are for ^{12}C projectile.

possible the conditions of the Ag–Cl experiment. No narrow peaks are seen in either this angular distribution or the one shown in Fig. 16 (plotted as dσ/dθ). These data are not selected for high multiplicity, and, therefore, do not exactly duplicate the conditions of the Frankfurt experiment.[24]

In an emulsion experiment, Otterlund et al.[28] have looked for evidence of shock waves produced by 0.2 and 2.0 GeV/nucleon ^{16}O ions. They are able to make cuts on charged particle multiplicity in this study of the angular distribution of all particles with energy loss greater than that expected for an 11 MeV proton. They

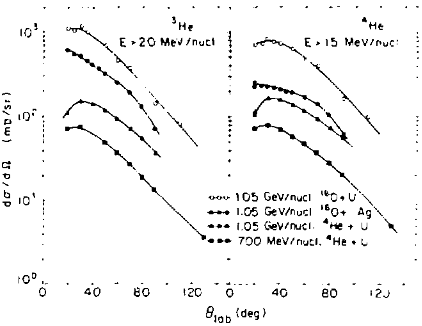

Fig. 15. Angular distributions of ^{3}He and ^{4}He fragments observed with ^{4}He and ^{16}O projectiles on Ag and U targets.

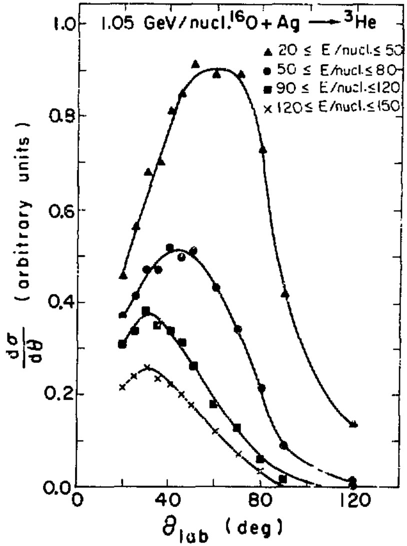

Fig. 16. Differential cross sections/unit angle, dσ/dθ, of ^{3}He fragments emitted in various energy windows between 20 and 150 MeV/nucleon from ^{16}O + Ag at 1.05 GeV/nucleon.

observed no statistically significant peaks in their angular distributions.

At present, there does not seem to be any overwhelming evidence for the existence of nuclear shock waves.[25] On the one hand, the Frankfurt group observes narrow peaks, but needs to greatly improve their statistics, as well as demonstrating that their detector sensitivity does not introduce any unwanted biases. The high statistics experiment of Poskanzer et al.[16] measuring only the single particle angular distribution, observes no peaks; but has no multiplicity cuts which can help select central collisions.[29] Emulsion work, where multiplicity cuts can be made sees no peaks, but also, could use an improvement in statistics.

PRELIMINARY RESULTS FROM STREAMER CHAMBER EXPERIMENTS

The LBL streamer chamber has recently been used to study nucleus-nucleus interactions by a U. C. Riverside/LBL collaboration.[6] The streamer chamber is a unique tool since it provides ~4π geometry and can be triggered electronically on events of interest. Four non-conducting targets (LiH, NaF, BaI_2, Pb_3O_4) have been placed in the chamber and exposed to a beam of 1.8 GeV/nucleon Ar nuclei. One of these interactions resulted in the spectacular interaction shown in Fig. 13. Again, it is worth noting that in this single event, the incident Ar nucleus appears to have been stripped down to its basic constituents. Large numbers of particles are seen at all angles, indicating that a large amount of energy and momentum can be distributed transversally in these collisions. Also note the absence of any large fragment of the projectile in the forward direction. It is also clear from Fig. 13 that the task of extracting all the information available in such pictures is staggering. However, one can initially provide such things as multiplicities for charged particles as well as concentrate on the finite number of negative tracks (presumably mainly π^-'s). Figure 17 shows preliminary multiplicity distributions for light and heavy targets. For the heavy target, multiplicities larger than 100 are observed. It is evident that there is a large cross section for high multiplicity events with the heavy target. The peaks at lower multiplicities can be associated with projectile fragmentation processes. In the near future, additional exposures will be made so that a series of systematic studies (as function of projectile mass and energy for both light and heavy targets) will be made.

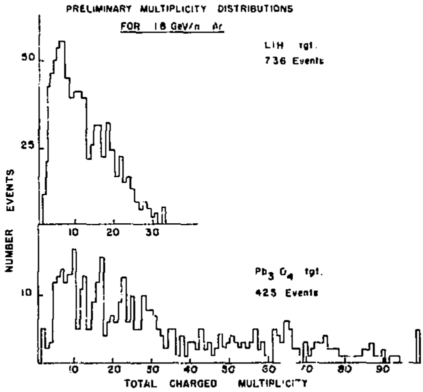

Fig. 17. Preliminary multiplicity distributions for positive and negative tracks produced by 1.8 GeV/n Ar projectile on LiH (upper graph) and Pb_3O_4 (lower graph) targets.

CONCLUSIONS

Studies of relativistic heavy ion interactions are being used to investigate details of nuclear structure (e.g., single particle momentum distributions), mechanisms for pion and γ-ray production, and the possibility of observing new states of nuclear matter. These experiments started as general surveys and are now in some cases in their second and third generations. Future emphasis will go into experiments involving single particle measurements with associated multiplicities, and studies of two and three particles (with correlations). With the ability to deliver large amounts of energy and momentum into a large volume (the nucleus), exciting new areas of physical investigation appear to be opening up.

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