Title
TOPICS IN RELATIVISTIC HEAVY-ION COLLISIONS

Author
Nagamiya, S.

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Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

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Shoji Nagamiya

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TOPICS IN RELATIVISTIC HEAVY-ION COLLISIONS

Shoji NAGAMIYA

Lawrence Berkeley Laboratory, University of California
Berkeley, California 94720, U.S.A.

The activities of the last few years in the field of relativistic heavy-ion collisions are reviewed. The current understanding of the reaction mechanism is described in the first part of the paper. In the second part, several recent topics are reported.

1. COLLISION GEOMETRY

Fragment spectra observed in relativistic heavy-ion collisions have the following general features. At 0° they are peaked at velocities equal to the beam velocity, while at large angles the spectra are essentially structureless and vary smoothly as a function of fragment momentum. The dominant yields at large angles are mainly from elemantary particles such as protons and pions, whereas at 0° several isotopes with mass numbers less than the beam nucleus are produced.

These observations readily suggest a simple picture of the collision geometry, as shown in Fig. 1. This is called the participant spectator model. After the collision the non-overlapped part between the beam and target nuclei, called the spectator, just keeps going without any interference. It produces a sharp peak at 0° with a velocity equal to the beam velocity. On the other hand, in the overlapped region, called the participant, strong interactions between the beam and target nucleons cause fragments to be emitted over a wide angular range. Fragments from this region are mainly elementary particles, because the energy transfer involved is much higher than the mutual binding energies of nucleons.

The average number of participant protons which come from the beam nucleus is proportional to the ratio of the target cross section to the total cross section:

$$\langle Z^{\mathrm{Participant}}_{\mathrm{Beam}}\rangle = Z_B\, A_T^{2/3}/(A_B^{1/3}+A_T^{1/3})^2. \qquad (1)$$

Similarly we have

$$\langle Z^{\mathrm{Participant}}_{\mathrm{Target}}\rangle = Z_T\, A_B^{2/3}/(A_B^{1/3}+A_T^{1/3})^2. \qquad (2)$$

The total yield of nuclear charge of the beam fragments is thus given by

$$\underbrace{(Z_B - \langle Z^{\mathrm{Participant}}_{\mathrm{Beam}}\rangle)}_{\text{Beam-spectator charge}} \cdot \underbrace{\pi r_0^2(A_B^{1/3}+A_T^{1/3})^2}_{\text{Cross section }(\sigma_T)}$$
$$= \pi r_0^2 Z_B(A_B^{2/3}+2A_B^{1/3}A_T^{1/3}), \qquad (3)$$

where $r_0 = 1.2$ fm. On the other hand, the total yield of nuclear charge from the participant piece becomes

$$(\langle Z^{\mathrm{Participant}}_{\mathrm{Beam}}\rangle + \langle Z^{\mathrm{Participant}}_{\mathrm{Target}}\rangle)\cdot \sigma_T$$
$$= \pi r_0^2(Z_B A_T^{2/3} + Z_T A_B^{2/3}). \qquad (4)$$

Formula (4) is given by Hüfner[1]).

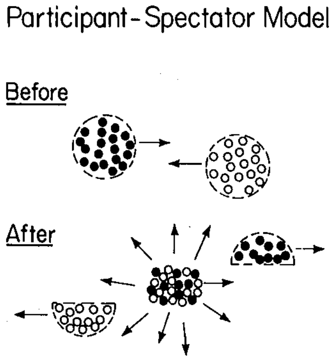

Fig. 1

In Figs. 1 and 2 the formulas (3) and (4) are tested. For beam fragments the experimental points shown in Fig. 2 were calculated from the data by Lindstrom *et al*[2]) who measured isotope yields at 0° for beams of C and O. The target mass (A_T) dependence of the yield goes like $A_T^{1/4}$, which is predicted by Eq. (3). The observed yields are about 2/3's of the predicted ones, but neverthless the simple geometrical picture explains rather well the beam fragments. Fig. 3 shows the sum of charges for p, d, t, and ^{3}He calculated from the data taken at $10° < \theta < 145°$ after extrapolation to 0° and 180°. Most are from the participant piece now, and the agreement with Eq. (4) is fair.

The above comparison tells us that the participant-spectator model describes reasonably well the geometrical aspect. The model is meaningful when the de Broglie wave length of the incident nucleons is shorter than the internucleon distance inside the nucleus; namely $\hbar/p \ll 1.8$ fm, which is satisfied for $E_{Beam} > 10\text{-}20$ MeV/A.

The geometrical aspects can further be studied by means of high-multiplicity events. We expect that high-multiplicity selects small-impact-parameter events.

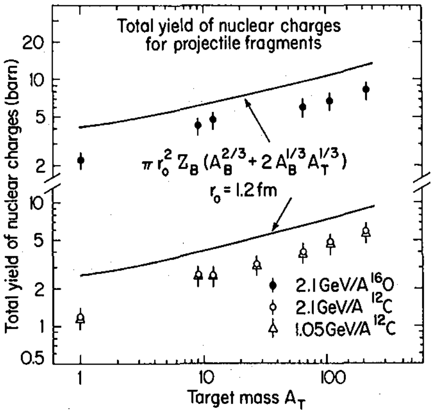

Fig. 2

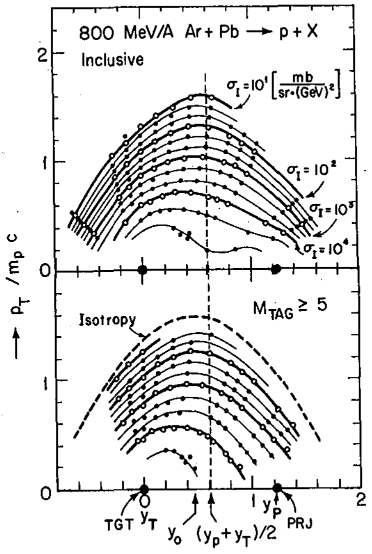

Fig. 4

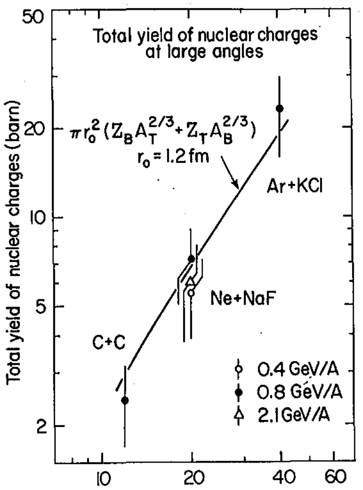

Fig. 3

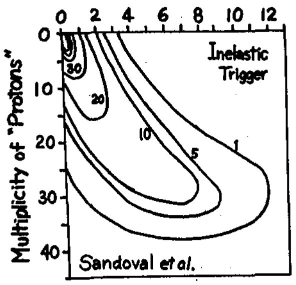

Fig. 5

Fig. 4 shows a comparison of the proton spectra between inclusive and high-multiplicity events in 800 MeV/A Ar + KCl. For inclusive events both beam and target fragments are observed in the small-p_T region, while for high-multiplicity events we observe target fragments only. For small impact parameters most of the beam nucleus (Ar) contributes to the participant, while the target nucleus (Pb) contributes to both the participant and the target spectator, because the size of Pb is larger than that of Ar.

When a beam nucleus is larger than a target nucleus, we expect a suppression of the target fragments for high event multiplicity. Such an evidence is reported by Bhalla *et al*[3]) in collisions of Fe + CNO. According to them, however, the yield of the beam fragments is not as much as expected from a simple geometrical consideration. This fact could be related to the observation seen in Fig. 3.

Sandoval *et al*[4]) have recently used a streamer chamber and selected extremely high-multiplicity events for collisions of Ar + KCl. As shown in Fig. 4, they observed higher pion multiplicities for higher proton multiplicity events. At a given proton multiplicity, which corresponds to a certain impact parameter according to the participant-spectator model, the pion multiplicity distribution is given by the Piosson distribution, as predicted by Gyulassy and Kauffmann[5]).

2. COLLISION DYNAMICS

One of major questions addressed in the last few years is related to the collision dynamics. In regard to the dynamics of the spectator, Goldhaber[6]) first gave a convincing argument, and since then several microscopic discussions have been deveoloped and reported[7-9]). In this Conference an interesting approach to the study of clustering feature of beam fragments is reported by Masuda and Uchiyama[10]).

However, the most excitingly hot discussion of the collision dynamics in the last few years has been concentrated on the participant region. Theoretically two extreme cases are easily handled: the clean knock-out (CKO) model[11-13]) and thermal model[14-16]). In this paper we discuss mainly the participant dynamics.

Fig. 6 shows proton and pion energy spectra at c.m. 90° for collisions of 800 MeV/A Ne + NaF. The c.m. 90° was selected, since particle emission at this angle is less affected by the spectator fragments. For protons the shape of the energy spectra is exponential at high energies but deviates from an exponential shape at low energies, while the shape of pion spectra is exponential at all energies. In addition, the slope of the pions is steeper than that for protons. In the figure two theoretical predictions are compared with the data; one from the single CKO model and the other from the thermal mosel by Sano[17]). Although neither model reproduces the detailed structure of the data, it is surprizing that they both expalin the gross features, including the absolute values.

In Fig. 7 the angular distributions of protons in the c.m. frame are plotted for collisions of 800 MeV/A Ar + KCl. The data show in general forward and backward peaking, but the ratio of forward to the 90° yield is not as large as the prediction of the CKO model. The thermal model should show an isotropic distribution, because there the multiple nucleon-nucleon collisions are dominant, and all the initial memory of the beam direction is lost. The data also deviate from it. Therefore, it is strongly suggested that the inclusive data are a mixture of two components, the thermal and CKO processes.

It is thus reasonable to assume that the particle yield, σ, can be written as

$$\sigma = \sigma_1 + \sigma_2 + \sigma_3 + \cdots , \qquad (5)$$

where σ_i describes the yield of particles emitted after i^{th} nucleon-nucleon scattering. The $i = 1$ term expresses the CKO process, and terms with large i's give the

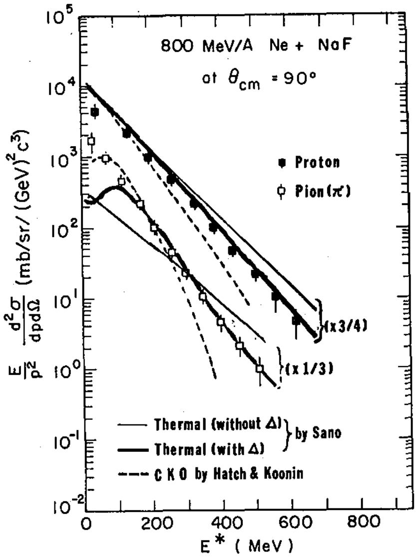

Fig. 6

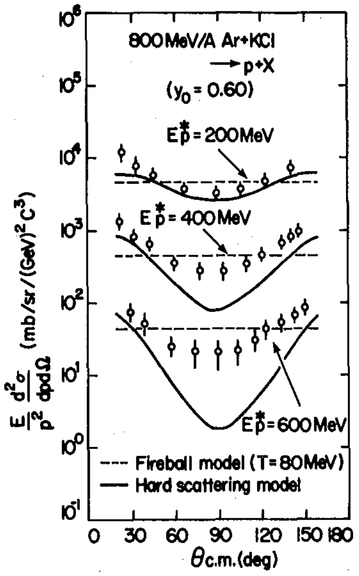

Fig. 7

thermal process. Experimental data shown in Fig. 7 suggest that each term of Eq. (5) gives a significant contribution to the particle emission. This can also be justified theoretically, since at relativistic energies the mean free path of nucleons inside the nucleus is 1 - 2 fm which is comparable to but shorter than the typical reaction size between colliding nuclei.

In this Conference, papers based on the CKO model$^{18)}$ and the thermal model$^{19)}$ are reported. Both approaches certainly describe certain aspects of fragment emission, but we should keep in minde that they do not describe all the aspects. Recently several models which effectively include aspects of both models have been developed$^{20-24)}$. In this regard, cascade calculations$^{25-27)}$ are the best example, although they are very complicated. In this paper, we further describe the roles of CKO and thermal components from an experimental point of view.

Two-proton azimuthal correlations provide a powerful tool to study the CKO component, since if the CKO process is domiant there are strong correlations due to p-p quasi-elastic scatterings$^{28-30)}$, whereas the statistical process causes very small correlations. Fig. 8 shows contour plots of the in-plane to out-of-plane ratios of the coincidence rates between two protons. The coincidence was taken by a magnetic spectrometer and a plastic counter telescope. The kinematical region covered by the in-plane telescope is indicated by a cross-hatched area in Fig. 8. The spectrometer covers a wide kinematical region. Data are presented in the palne of the parallel and transverse momenta of the emitted protons in the nucleon-nucleon c.m. frame. The ratios have a peak on the circle but on the side opposite the cross-hatched area, where the circle indicates the p-p elastic scatterind kinematics when the internal motion of nucleons inside the nucleus is ignored [Note that two points, P and T, represent beam and target momenta per nucleon.]. We thus clearly observe the p-p quasi-elastic scatterings in heavy-ion collisions.

From the peak height the fraction of the single CKO process can be estimated. The in-plane correlation comes from a single pair of two protons scattered elastically, while the coincidence rate between two protons in general is proportional to the total event multiplicity. Therefore, the in-plane to out-of-plane ratio decreases as the event multiplicity increases. Detailed calculated results are shown in Fig.

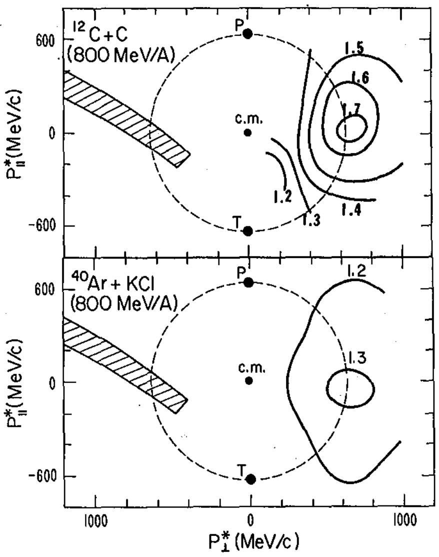

Fig. 8

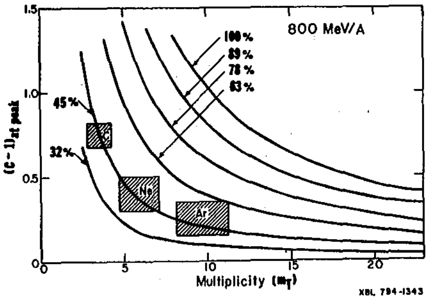

Fig. 9

9, where the deviation of the ratio, C, from 1 at the peak point of C is plotted as a function of the event multiplicity, m_T. Curves are labelled according to the percentage fractions of CKO processes, σ_1/σ. Cross-hatched areas indicate experimental points for C + C, Ne + NaF, and Ar + KCl. From the figure we see that for protons emitted at $\theta^{c.m.} \sim 90°$ with c.m. energies $E^{c.m.}_{\mathrm{Proton}} = E^{c.m.}_{\mathrm{Beam}}/A$ ($\simeq$ 182 MeV/A in this case), half are from the CKO processes.

Another tool for studying the contribution of the various σ_l's of Eq. (5) is the measurements of high-multiplicity events, since then a larger overlap between beam and target is expected and fragments are likely to be emitted from multiple nucleon-nucleon scatterings. In Fig. 10 the proton yields for both inclusive and high-multiplicity events are plotted for collisions of 800 MeV/A Ar on KCl and Pb, as a function of the angle in the effective c.m. frame of the participant piece. Three sets of energies of emitted protons are selected: 200, 400, and 600 MeV as measured in that frame. We observe that the angular distribution is more isotropic for high-multiplicity events than for inclusive events, indicating that the high-multiplicity events are mainly from multiple scatterings. If we simply assume that the high-multiplicity events represent the contribution from multiple scatterings and further assume that the inclusive spectrum is a superposition of the clean CKO component (σ_1) and the observed proton spectrum of high-multiplicity

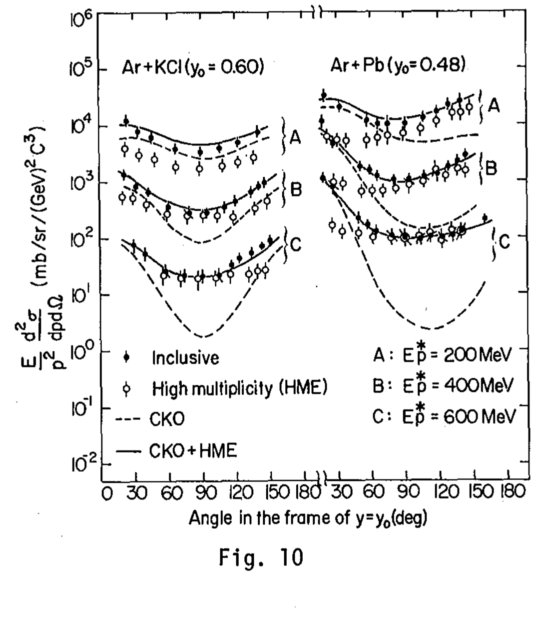

Fig. 10

events, then we can calculate the inclusive yield by using the previously calculated values of the CKO component[13]. This is shown by the solid curves which are in good agreement with the observed inclusive data. A fair agreement thus implies that the assumptions applied here may not be so bad. If so, then we learn several things: (1) The contribution from the single CKO process is very small for high-energy protons at 90°. Namely, large p_T events are mainly from multiple scatterings. (2) At small angles the CKO component is dominant even for high-energy protons. (3) For protons with $E_p^* = 200$ MeV at 90° the fraction of the CKO component (σ_1/σ) is about 0.6. This result is consistent with the result of the two-proton correlation data, since there we found $\sigma_1/\sigma \simeq 0.5$. Although the discussion presented here is rather crude, we can nevertheless learn from the particle correlation data the relative importance of the thermal and CKO components over a wide kinematical region of the emitted protons. The observations described above are summarized in Fig. 11.

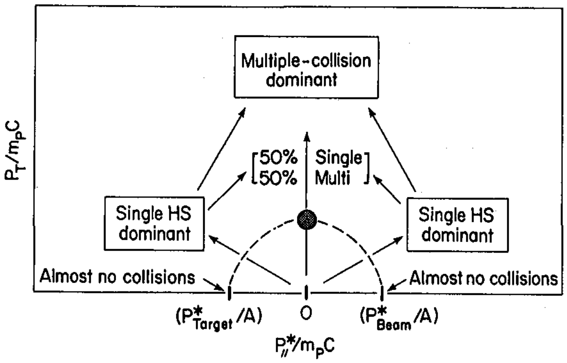

Fig. 11

3. SOURCE SIZE OF FRAGMENT EMISSION

In the past few years several theorists[31,32] have suggested a measurement of the Hanbury-Brown/Twiss effect[33] in heavy-ion collisions. This is an interference effect between two particles. There is a strong interference if two particles are emitted with the same momentum. However, the degree of interference is small if they are emitted from a source with large dimension. Similarly, the interference disappears when they are emitted independently in time. Thus, the source radius and reaction time can be determined from the interference pattern.

The first experimental evidence of this effect in heavy-ion collisions was reported by Fung *et al.*[34]. They observed interference patterns between two π^- fragments in a streamer chamber, as shown in Fig. 12, and obtained the reaction time of 5 × 10^{-24} sec and the source radius of 3.3±0.9 fm for 1.8 GeV/A Ar + Pb$_3$O$_4$. For high-multiplicity events an even larger value of the radius is observed. According to the participant-spectator model, the average radius of the participant for Ar + Pb is 4.2 fm for normal density matter, which is close to the observed radius. At this Conference, Bartke *et al*[35] reported that the radius of 3.3±0.6 fm was obtained in their 2 π^- measurements in 3.4 GeV/A C + Ta.

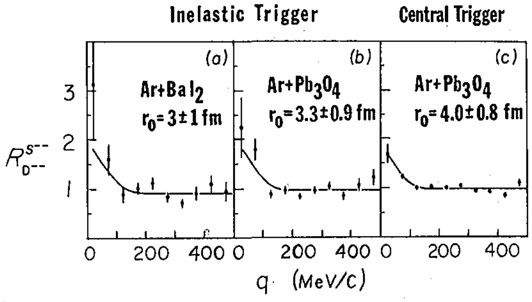

Fig. 12

Besides the Hanbury-Brown/Twiss effect, Mekjian[15] pointed out that the source size can be determined from a comparison of the composite fragment spectra with the proton spectra. According to the phase-space arguments, the probability of producing a deuteron at a velocity $\vec{v}_d$ is proportional to the probability of finding a proton and a neutron at the

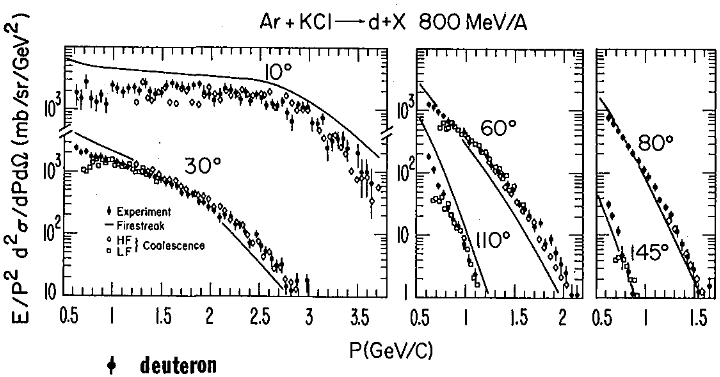

Fig. 13

same velocity:

$$P_d(\vec{v} = \vec{v}_d) \propto P_p(\vec{v} = \vec{v}_d) \cdot P_n(\vec{v} = \vec{v}_d), \qquad (6)$$

where $P(\vec{v})$ is the probability of a particle having the velocity $\vec{v}$. This is the well known idea of coalescence[36,37]), sometimes called the final state interaction. Such a prediction is tested in Fig. 13 over a wide kinematical region of the deuteron spectra[38]), where the neutron spectra are assumed to be the same as the proton spectra. The prediction works very well. The ratio of deuterons to $(\text{protons})^2$ is directly related to the source volume, because, if the volume is large, there is less chance for the proton and neutron to coalesce, with the result being a smaller yield of deuterons. The source radius evaluated from the data, using the formula of Mekjian[15]) is presented in Fig. 14. We obtain 3-4 fm as a source size, which is comparable to the value obtained from two-pion interferrometry.

Meng Ta-Chung[39]) recently reported that even the inclusive spectra of pions can give the value of the source radius. If we assume that the pion source is a system of bosons in thermal equilibrium, then the total energy carried out by the pions is proportional to the source volume, provided that the temperature is fixed. He evaluated the radius to be 3.7 fm for collisions of 800 MeV/A Ne + NaF.

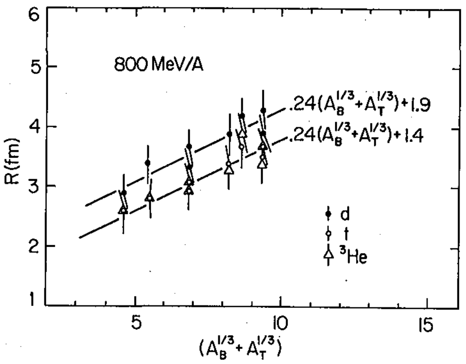

Fig. 14

Source radii obtained with these three methods are in reasonably good agreement with each other. However, whether or not the radii determined by these methods represent the same physical quantity is questionable. Obviously further careful analysis has to be done to answer this question.

4. LOW-ENERGY PIONS

Fig. 15 shows π^+ and π^- spectra at 0° as measured by Benenson *et al.*[38]) in collisions of 400 MeV/A Ne + NaF. The yield of π^- has a sharp peak at the beam velocity, while that of π^+ shows a dip. According to their recent measurements[41]), the peak position of π^- is always found at the beam velocity at all bombarding energies between 300 and 500 MeV, with angular width less than ±5°. Furthermore, the

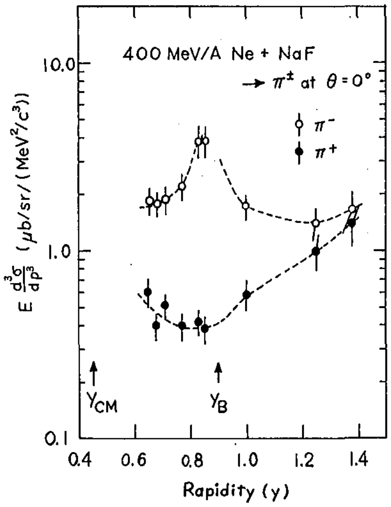

Fig. 15

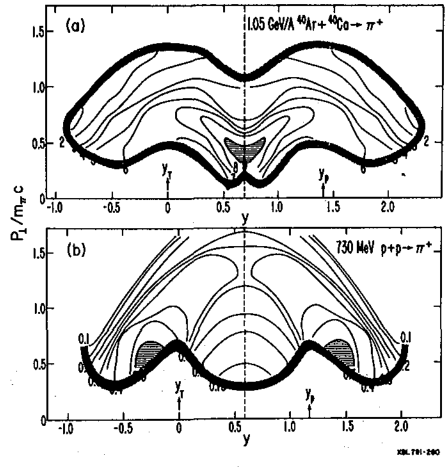

Fig. 16

peak is more pronounced for lighter-mass targets. Such phenomena are most likely due to the Coulomb effect. There is a high probability for pions or Δ's produced inside the beam spectator or participant region to be rescattered by the beam (and target) spectator, so that the spectator behaves like a new pion source. The Coulomb barrier tends to prohibit the low-energy π^+ emission, while very low-energy π^- can be emitted. One interesting application of this result is the use of heavy-ion beams as a π^- beam source of monochromatic energy. In this application the π^- beam energy can be controlled by the incident heavy-ion beam.

Another interesting topic concerning low-energy pions is an enhancement of the π^+ yield at c.m. 90° for collisions of Ne + NaF [ref. 42)] and Ar + Ca [ref. 43)] at beam energies around 0.8-1 GeV/A. Such an enhancement is observed at $p_T \sim 0.5\ m_\pi c$, and is independent of the fragment multiplicity. Furthermore, it is not observed at beam energies below and above ∿1 GeV/A. In Fig. 16 a typical result is shown and is compared with the data of $p + p \rightarrow \pi^+$. The peaking is specific to heavy-ion collisions. Explanation of this peak is not yet available, but there are several suggestions, such as its being due to the Coulomb effect44), the blast wave45), or two Δ-sources inside the beam and target spectators. It encourages further measurements of both π^+ and π^- using a magnetic spectrometer.

5. NEW NEUTRON-RICH ISOTOPES

According to the participant-spectator model, the mass to charge ratio (A/Z) of the beam spectator remains the same as the initial A/Z ratio of the beam nucleus. Therefore, at the initial stage of the collision masses of beam fragments are distributed toward both the neutron-rich and neutron-deficient sides with their center around $(A/Z)_{\text{Beam}}$. If we use neutron-rich nuclei as beam particles, then we can produce many neutron-rich nuclei from beam fragments.

Symons *et al.*46) recently discovered about 14 new neutron-rich isotopes in the beam fragments of ^{48}Ca beams. This type of study will open up a wide range of applications of relativistic heavy ions to nuclear physics studies. For example, the region far from the nuclear stability line up to $A/Z \sim 3$ can be studied. New regions of deformation may be found, or the Coulomb effect may cause a large difference between mass and charge radii. One fascinating idea is the use of such neutron-rich isotopes as secondary beams to dig out much more nuetron-rich regions.

6. HINTS OF COMPRESSION

One of the initial goals of relativistic heavy-ion research was to discover dense, highly excited nuclear matter. So far, no concrete experimental evidence for the existence of dense nuclear matter has been observed. However, there are a few hints to suggest that there may be nuclear compression.

An extensive study of emulsions has been carried out by the Frankfurt group to study Mach cones due to shockwaves. Some of their new results are reported by Baumgardt and Schopper[47]) at this Conference.

Gutbrod *et al*[48]) have recently reported that proton angular distributions have a peak at around 30° for high-multiplicity events in 400 MeV/A Ne + U. Although the results are still preliminary, if this observation is correct, then it may suggest sideward hydrodynamical flow, or it may indicate the presence of a Mach cone. Their preliminary data are shown in Fig. 17.

Siemens and Rasmussen[45]) have analyzed proton and pion spectra at large angles. As shown in Fig. 18, the best fit to the data can be obtained if one assumes an explosion flow (blast wave) from the compressed matter. This may give a further hint of compression.

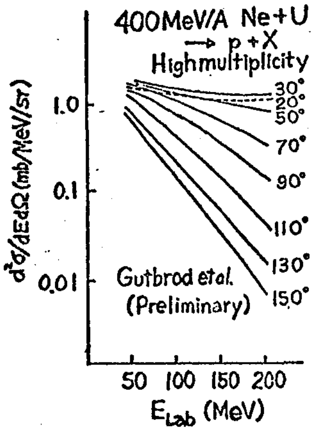

Fig. 17

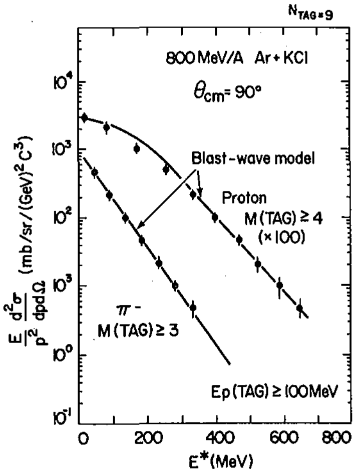

Fig. 18

7. SPECTATOR-SPECTATOR OR SPECTATOR-PARTICIPANT INTERACTION

Spectator-spectator interaction is a subject related to heavy-ion elastic and inelastic scatterings. At relativistic energies the interaction potential between heavy-ions is not very well known, and its study is a very interesting subject. In fact, at this Conference 5 or more contributed papers on this subject are being presented.

The spectator-participant interaction has not been studied well. One interesting subject which is related to this interaction is the frictional force between them, which gives a certain amount of angular momentum to the beam and target spectators or even to the participant region. Measurements of the polarization of beam (and target) fragments are very interesting and have yet to be done. The Coulomb interaction should also be carefully tested. It usually causes a wider momentum distribution of beam fragments toward the transverse direction than toward the longitudinal one.

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TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720