Title
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1. Introduction

Collisions of heavy nuclei have become one of the main subjects of research in nuclear physics in the past decade. The bulk of the experimental and theoretical effort in heavy-ion collisions has, quite naturally, concentrated on the more readily accessible collisions of non-relativistic nuclei. Five years ago, however, the ingenious plan of using the Hilac at Berkeley as an injector for the venerable Bevatron led, at one jump, to a hundredfold increase in the energy of available intense beams of heavy nuclei. At about the same time, low-intensity beams became available at Dubna at twice the Bevalac energy. Now many accelerators are being built, planned or proposed to make available beams of heavier nuclei at greater intensities and with higher energies.

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The main motivation for studying high-energy heavy-ion reactions has been the hope of creating and studying nuclear matter at high density and high excitation energy. In a head-on collision of large nuclei, repeated collisions among the constituents of the target and projectile could lead to a sharing of the projectile's momentum and kinetic energy with matter from the target. If the reaction could be made to take place within a box of nuclear dimensions, multiple collisions would eventually lead to a thermalization of the incident energy. Since we cannot fabricate such a box, we have to hope that the dynamics of the nuclear collisions will, at least briefly, lead to concentration of many baryons and much energy in a small region of space. Thus, we are hoping for an inertial-confinement mechanism to lead to the production of hot, dense matter.

The formation of hot, dense matter is not the only thing that can happen when nuclei collide. They may miss each other entirely and continue on only slightly deflected, and perhaps gently excited, by the fringes of the coulomb and strong-interaction fields surrounding them. Or individual nucleons may collide with each other much as they would in the absence of the other nucleons. These processes are interesting in their own right, and can be used to obtain information about nuclear structure and spectra that can't be learned from low-energy data. But they also complicate the problem of identifying and studying the hot, high-density matter, especially because several different reaction mechanisms may be at work in the same collision. This has made the job of unravelling the measurements very difficult.

It isn't surprising, then, that we don't yet know much about the hot dense matter. The difficulty of interpreting the measured speeds and directions of the many different reaction products is almost as great as the difficult of measuring them. Individual events may have a hundred or more particles in the final state, and these have to be identified as protons, pions, or heavier nuclei. After measuring their velocities, they have to be classified according to the mechanism by which they are produced. Finally, the measured cross sections have to be interpreted to deduce properties of nuclear matter and nuclear structure. From these properties, as well as what we learn about the reaction mechanisms and dynamics, we may, if we are lucky, learn something fundamental about the nature of hadronic interactions.

This report attempts to give a snapshot of the state of the art of unravelling this puzzle of high-energy nuclear collisions.

scattered, while other portions are relatively undisturbed. A simple description of these collisions is provided by the participant-spectator model. Participant nucleons are those which have suffered a large momentum transfer, spectators have received little or no change of momentum. This distinction may be considered as an operational definition. Remarkably, the numbers of participant and spectator nucleons for a given target-projectile combination is, within errors, independent of the beam energy from 400 MeV to 2 GeV per nucleon. This suggests a geometrical interpretation: the spectators are those nucleons in the target or projectile whose straight-line trajectories would miss the other nucleus, the rest are participants. Simple geometry then leads to the prediction(1)

$$\sigma_{\text{part}} = \pi r_o^2 (Z_p A_t^{2/3} + Z_t A_p^{2/3}) \qquad (1)$$

for the total cross section for participant protons, in good agreement with experiment (Fig. 1) for collisions where the target and projectile have similar sizes. In comparing experiment to eq. 1, one must of course remember to count those protons which appear in deuterons and heavier fragments.

It is perhaps surprising that eq. 1 gives such a good prediction of the number of participants, when we consider what is left out of this very simple picture. On the one hand, participant nucleons can scatter into the spectator matter, where they can knock out more nucleons to increase the number of participants. On the other hand, some of the projectile nucleons would be expected to go right through the target without much momentum transfer, particularly at higher energies where the nucleonic cross section is strongly forward peaked. Evidently, these two effects approximately cancel when the target and projectile are about the same size and are not too heavy (the experiments cover $A_p \leqq 40$). If the target is much larger than the projectile, we should expect the number of participants to be greater than given by eq. 1. For such unequal systems, the distinction between participants and spectators is probably rather blurred, as each of the original participants may have to share its momentum with a number of the surrounding spectator nucleons.

3. Spectator matter

One of the earliest systematic observations of high-energy heavy-ion reactions was the distribution of the energies of projectile-like fragments,(3) which have a Gaussian velocity distribution centered about a velocity slightly less than the beam's. The widths of these distributions are explained by Goldhaber(4) using a simple picture due to Feshbach and Huang(5) in which the target slices off a piece of the projectile, containing nucleons whose momenta are randomly selected from the Fermi sea. The same picture explains the width in transverse momentum, when proper account is taken of the Coulomb deflection.(6) The shift in the mean longitudinal momentum is less than the width of the distributions, and is probably due to the occasional participant nucleon--which has less longitudinal velocity on the average--lodging in or scattering from the projectile fragment. It seems that the effect of the participants on the spectator matter is indeed rather small. Incidentally, this is equally true at 20 MeV per nucleon.(7)

Having confirmed the validity of the participant-spectator model, we can use the peripheral collisions to tell us interesting information about nuclear structure. One property that hadn't been measured before is the bulk isospin correlation in the nucleus: what is the probability that, if you chop off A nucleons, Z of them will be protons? The measured width of the isotope distributions(8) is narrower than it would be in the independent-particle model(9) but can be explained by collective isospin correlations due to the isospin dependence of the nuclear forces.(10) Investigations of the evaporative cascade of excited projectile fragments, now in progress, will tell us more about the mechanism of the reaction. And even though the isospin distributions are narrowed by correlations, they are still broad enough to produce lots of new isotopes.(11) As experimental techniques advance, we may expect the Coulomb field or the periphery of the nuclear field, to excite high-lying collective vibrations which cannot be excited directly in any other way.

For a while it was hoped that the passage of the participant region would excite coherent compression waves of large amplitude in the nearby spectator matter.(12) In the idealized geometry of the participant-spectator model, these waves would come off at at the Mach angle $\theta_m = \cos^{-1} \beta_o/v_1$ where v_1 is the speed of the shock fromt and approaches the speed of sound for small-amplitude disturbances. Unfortunately, this very interesting prediction seems to be an artifact of the oversimplified geometry, and appears neither in more sophisticated models (discussed below) nor in the current data. If the hope of creating high-density nuclear matter is to be realized, we must look to the participant matter.

4. Thermalization of participant matter

The simplest picture of the participant matter was proposed by Hatch and Koonin:(13) every participant nucleon scatters just once from another participant. This picture, called Clean Knockout or CKO, is similar to that proposed for backward scattering of protons from nuclei.(14) By folding the cross section for nucleon-nucleon elastic scattering with the momentum distributions posited to explain backward p-nucleus scattering, they find good agreement with measured cross sections for protons from C+C and Ne+NaF at 800 MeV per nucleon, in the region of large momentum transfers. Both the absolute value and momentum dependence of the cross sections are adequately described, when the collision kinematics are chosen to take account of an average potential energy of 40 MeV per nucleon. The CKO claims additional support from the apparent symmetry of high-transverse-momentum cross sections abut the center-of-mass velocity (Fig. 2). It also predicted that a nucleon of large transverse momentum would often be accompanied by another of equal and opposite momentum in the nucleon-nucleon center of mass. This prediction has recently been verified (Fig. 3). From the enhancement in the ratio of in-plane to out-of-plane p-p coincidences, Nagamiya(15) estimates that about half the protons in the trigger counter (shaded region in Fig. 3), come from the CKO process. This estimate is the same for C+C and for Ar + KCl; the larger correlation seen in the lighter system is attributed to the smaller background from uncorrelated pairs, rather than a decreased likelihood of multiple collisions.

It seems clear that there must be a significant component of CKO protons in the observed spectra. The bulk of these are not very interesting, namely those which can be produced by quasi-elastic scattering of nucleons inside the Fermi sea. We can call these nucleons quasi-elastic, or QE. Their main interest lies in the fact that they obscure the observation of the nucleons with a more interesting history. To minimize the proportion of knock-out nucleons, we can look selectively at collisions in which many nucleons are produced with a large transverse momentum.

The fact that the high-transverse-momentum nucleons are nearly symmetric in the nucleon-nucleon cm does not distinguish between CKO and multiple-collision protons: the latter might be expected to be symmetric in the cm of the participant matter (y_{FB} in Fig. 2), too close to the nucleon-nucleon cm to be distinguishable on the basis of the data.

Nagamiya et al., have collected data in which several tag counters are placed at various azimuthal angles, each covering a region of momentum and scattering angle like the shaded area in Fig. 3. When they insist on several of these tag counters firing, they observe that the proportion of protons at very large transverse momentum--outside the quasi-elastic region--increases strongly. Conversely, the observation of a non-QE proton at high transverse momentum is associated with a much higher tag multiplicity than protons of low transverse momentum (Fig. 4). Thus, high-transverse-momentum protons are associated with central collisions. This could be explained in the CKO model by the lack of spectator matter in central collisions. However, even in unselected data, the CKO model predicts an order of magnitude greater forward-backward peaking than observed for protons of 600 MeV cm kinetic energy in 800 MeV/nucleon (182 MeV cm) Ar + KCl (Ref. 15). Furthermore, cascade computations show that most of the nucleons which scatter at least once scatter several times (Fig. 5). Also, Chemtob and Schurmann have shown(16) that taking the nucleons off their mass shell decreases their scattering to large transverse momentum. Since we expect the high-momentum components of the nuclear wave function to be due to short-range correlations, they should be much farther off-shell than Hatch and Koonin's 40 MeV, making their prediction an overestimate. Finally, it is by no means clear that the backward p-nucleus scattering is CKO, though that may be somewhat irrelevant as it is equally disappointing to reduce heavy-ion spectra to p-nucleus as to p-p.

Nagamiya(15) has demonstrated that a consistent picture of the inclusive proton spectra is found by taking about half the prediction of the CKO model and adding a similar number of protons distributed like the high-multiplicity central collisions. The high-multiplicity component dominates completely the region of large transverse momentum outside the quasi-elastic regime. In view of the arguments above, it seems likely that these latter protons come from multiple collisions rather than clean knock-out in a single step. Thus, they are the most promising place to look for information about the properties of hot, dense nuclear matter.

The natural generalization of the CKO model is to include repeated collisions of the nucleons in a Monte Carlo cascade. By assuming straight-line trajectories for the nucleons between collisions, the geometry can be taken into account in a plausible manner. For the lowest beam energies (less than about 500 MeV per nucleon) very few pions are formed, so inelastic collisions may be neglected. Figure 5 shows the result(17) of such a computation for a typical collision of $A_t = A_p = 40$ at 400 MeV/nucleon laboratory kinetic energy, with an impact parameter equal to the radius of one of the nuclei. First, we see that the participant-spectator geometry is well confirmed: 60% of the nucleons pass undistrubed, exactly the prediction of the participant-spectator model. One-fifth of these are from the geometrical region where they would have to pass through nuclear matter, but they are exactly compensated by peripheral nucleons struck in secondary collisions. Of the 40% of the nucleons which suffer at least one collision, nearly all (five sixths) collide more than once, in fact four times on the average. Of the few that escape with only one collision, half are from the spectator matter and thus not part of the CKO process. (It may be worthwhile to remark in passing that this result can only be obtained from a full cascade computation.(17-20) An oft-cited adaptation of a popular proton-nucleus cascade code(21) requires a virgin partner for each scattering, and thus gives at least 50% CKO).

Since the participant nucleons collide so many times, it is not surprising that the cascade computations in this energy regime predict that the initial kinetic energy along the beam direction is quickly redistributed into transverse motion. In other words, the matter appears to be thermalized even before the spectator matter has departed from the interaction regon. Empirical evidence for this theoretical prediction is given by the observation that the (relatively few) pions produced in the collisions are strongly affected by the Coulomb field of the spectator fragment from the projectile,(22) illustrated in Fig. 6. This beam energy is so low that far fewer pions can be produced in the first collisions of nucleons inside the Fermi sea, than are observed at 0°. Thus, the pions must come from collisions of nucleons which have already collided to achieve a large enough relative velocity. Indeed, the magnitude of the cross sections is consistent with the pions being produced in thermal equlibrium in the hot matter. The great magnitude of the influence of the projectile fragment's Coulomb field shows that the thermalization must occur before the projectile fragment has moved away. A similar conclusion follows from two independent computations in which the long-range attractive and short-range repulsive forces between the nucleons are permitted to bend the nucleons' trajectories according to classical equations of motion.(23,24) Both the classical-orbit and cascade computations indicate that the equilibration happens when the matter is compressed to about double the density of normal nucleus, for collisions of equal target and projectile at beam energies around 400 MeV per nucleon in the laboratory.

At higher beam energies, the theoretical models are less satisfactory, because the production of pions becomes very important. For example, at 800 MeV per nucleon beam energy about half the nucleon-nucleon collisions lead to production of a pion. The number of pions observed per proton at 90° c.m. for Ne on NaF at this energy is about 0.6 of what would be expected from free nucleon-nucleon production, indicating that about 20% of the kinetic energy of the thermalized nucleons has been used to create and accelerate pions. At the top Bevalac energy of 2.1 GeV per nucleon, the same comparison shows nearly as many pions as nucleons (about 2/3). The creation of pions by the isobar mechanism is an excellent means of stopping the nucleons, and thus thermalizing their kinetic energy. The pions produced by this mechanism have large, resonant cross sections for rescattering from nucleons, so we should expect their kinetic energy to be thermalized too. In fact, the positive pions produced in 800 MeV per nucleon Ne on NaF(25) and 1.05 GeV per nucleon Ar on Ca(26) (Fig. 7) show little trace of the isobar kinematics, and even have a maximum at 90° c.m. for low energy pions, where the direct isobar production has a minimum. Unfortunately, none of the existing cascade codes treat the rescattering of pions in a plausible way, so we cannot rely on them as a guide to the thermalization process at energies where pions have a significant part of the energy. Indeed, it seems likely that even a careful treatment of pion rescattering in a cascade model would underestimate the pionic influence on the thermalization process, since long-range fluctuations of the pion field may greatly enhance the scattering of nucleons in dense nuclear matter, as pointed out by Gyullassy and Greiner.(27) The most reasonable treatment of pion degrees of freedom reported to date is that of Toneev and Gudima,(28) who introduce an energy-independent absorption. They find a rapid equilibration of the local momentum distributions for Ne + U collisions, even up to 2.1 GeV per nucleon beam energy. Compressions obtained in their model exceed a factor of three over normal density.

The cascade models, together with their cousins the classical-trajectory models, are probably the most important theoretical method applied so far to heavy ion collisions at high energy. They establish that we can reasonably expect to attain a thermalization of the kinetic energy of the beam, which is far from obvious in view of the very small size of the nuclei involved compared to the mean free paths. The main drawback of these models (aside from unnecessary approximations introduced for technical reasons) is their essentially two-body nature. Collective effects, three-body interactions, and other interesting processes--indeed the very effects we hope to observe--can be treated in only a crude and restricted way. Clever generalizations of these models may enable them to treat specific many-body effects (for a good example see Ref. 29). Meanwhile, we can take advantage of the encouraging results of these models to obtain simplified treatments which are more easily generalized to include the exotic phenomena we are hoping to discover.

An especially promising approach is that of Pirner and Schurmann,(30) who use the Boltzmann equation--with its obvious similarities to the cascade model--to derive a diffusion equation of Fokker-Planck type for the distributions of momenta and densities. Such diffusion equations can also be constructed from much more general models. While their treatment of pions in the first paper is too primitive to allow meaningful criticism of the data, the approach is potentially very powerful. In view of the great promise of the method, it would be useful to compare it with a cascade computation as soon as possible, using some test cases to establish the relation of the two methods.

The ultimate simplification of such a transport model is hydrodynamics, which can be thought of as a limiting case of the transport theory in which the deviations fom local equilibrium are treated as a linear perturbation. This means that at every time, the system of interacting particles is characterized by density, velocity and temperature fields, each a function of position. If we think of this as an approximation to the cascade computation, these quantities are just the first three moments of the distribution of particle velocities in each unit cell of position space. More generally, one can introduce the stress tensor but this is a familar topic from undergraduate physics and doesn't need to be explained here. The advantage of the hydrodynamic approximation lies not so much in ease of computation (which is actually hard if you go beyond simple analytically-soluble geometry), as in the great generality of the method which is not restricted to weakly-interacting or low-density systems. Again, there is an urgent need to compare some realistic cascade codes with the corresponding hydrodynamic approximations to verify the reliability of the latter. Lacking this, we can use the fact that cascade codes predict a rapid local equilibration to argue that hydrodynamic pictures should be reasonable, at least after the initial thermalization has taken place. We have to remember that, once you get to local equilibrium, hydrodynamics remains valid as long as the collisions are frequent, since it correctly describes the effects of small deviations from local equilibrium, including the tendency to re-establish it.

While numerous investigations show the usefulness of the equilibration concept at sub-pionic energies, and Toneev et al. extend this to the highest Bevalac energy, it is very interesting to wonder up to what energies the equilibration is sufficiently rapid to allow hydrodynamic phenomena to be seen. Sobel et al. argue that the approximations may begin to falter for beam energies greater than 1 GeV per nucleon, but the investigatons of Toneev et al. suggest that this is too pessimistic. The reason trouble is anticipated at higher energies is that the momentum transfer in hadronic collisions does not keep pace with the total relative momentum of the colliding hadrons. Thus, it should take more and more collisions to establish thermalization. Sobel et al. refer to this as the loss of stopping power of nuclear matter. A more optimistic assessment by Goldhaber(32) suggests that equilibration might be possible up to center-of-mass kinetic energies of 1 to 4 GeV per nucleon. We await with great interest the results of recent Dubna experiments at 4 GeV per nucleon in the lab, reported in this conference. A better understanding of proton-nucleus reactions would also be very helpful in deciding how optimistic we should be about making ultrahot nuclear matter with the 10 to 20 GeV beams and colliding rings now being proposed. A naive prejudice would expect that the nuclei will essentially pass through each other at such high energies, knocking out a few protons and peripherally producing lots of soft pions but not nearly enough to stop the matter and permit a general sharing of the energy.

A particularly interesting feature of the hydrodynamic approximation is that it permits a simple analytical computation of the compression attainable in a head-on collision of equal nuclei with a given beam energy. By following a small bit of matter as it stops and is heated, the conservation of baryon number, energy and momentum--which has to change by the difference in pressure--lead to a constraint among the thermodynamic variables describing the matter.(31) This constraint, called the Hugoniot relation, determines the division of the initial energy into mechanical energy of compression versus thermal energy of heating. Again, a detailed comparison with cascade and classical-trajectory models would be enlightening. The fact that Toneev gets greater compression than other cascade computations could be traceable to the difference in the equations of state implied by their models, since Toneev does not treat the (3/2,3/2) resonance explicitly.

5. Disintegration of the hot matter

Once the initial compression and thermalization has taken place, repeated collisions lead to an expansion of the hot dense matter which is conveniently described in a hydrodynamic picture.(31,33) This can be seen clearly in a hydrodynamic computation, Fig. 8 (Ref. 34). It is also observed in the cascade computations, as observed by Toneev(28). For central collisions of nuclei of very different sizes, this explosion occurs inside the heavy nucleus, making simple analysis difficult. When target and projectile have similar dimensions, the expansion occurs in free space and is thus largely reversible, so that little additional entropy is generated. The additional phase-space due to the expansion of matter into a larger region of position space is compensated by the shrinking of the velocity distribution into a smaller region of momentum space as the expanding matter cools. The loss of thermal and compressional energy works to accelerate the matter outwards, creating an explosion. This hydrodynamic expansion continues until the density of particles has become so small that they seldom collide. During this stage, the matter is no longer described hydrodynamically because the distribution of moments at any given position and time cannot be characterized by a mean velocity and a thermal fluctuation. The momentum distribution, however, remains the same when integrated over the particles' positions. The cessation of collisions may be called the momentum freezeout. Indeed, the measured momentum distributions of protons, pions and deuterons at 90° cm in central collisions can be characterized by a radially-shifted Boltzmann distribution,(33) Fig. 9.

The integrated energies are equal to the beam energy, but the radial blast motion leads to a cooler distribution than would be predicted from complete equipartition of energy (the fireball model, Ref. 35). As the matter expands and cools, pions are reabsorbed and resonances de-excited. Thus, the repeated collisions during this phase eliminate many of the signs which have been suggested as indicators of the properties of hot matter.

To learn about the properties of the matter, we have to look for some quantity which is conserved during the expansion and cooling. Baryon number, charge, energy and momentum tell us how much matter is involved and confirm the thermalization, but give no clues about the properties of the hot dense phase. S, the entropy per baryon of the matter, on the other hand, is sensitive to the properties of the matter and is nearly conserved during the hydrodynamic expansion. Since the binding energy of deuterons is small, their equilibrium number is determined by the phase-space density $\langle d_N \rangle$ of neutrons and protons, and hence by the entropy: the ratio of deuterons to protons is $R_{dp} = 12 \langle d_N \rangle = \exp(3.95 - S)$. Since, according to Liouville's theorem, the mean phase-space density $\langle d_N \rangle$ is also constant in the collisionless regime, and since R_{dp} is determined by detailed balancing, it doesn't matter that deuterons are destroyed and reformed during the expansion, even after momentum freezeout--their number is determined by the initial entropy of the hot dense matter.(36) The observed deuteron abundances are less than expected from an equation of state without phase transitions and incorporating nucleons and pions with their free-space masses along with a density-dependent potential energy. This means that something unexpected has happened already with beams of 400 to 800 MeV per nucleon! The extra entropy means that the nuclear matter has found more phase space than expected in the most optimistic non-exotic model (Fig. 10). Perhaps this is because there is a lot of extra potential energy in attractive interactions,(37) which would allow more of momentum space to be populated by the nucleons. Perhaps baryonic excited states are populated copiously, as proposed by Glendenning and Karant.(38) Perhaps pions of large momentum have an anomalously low energy in dense nuclear matter, as mentioned by Ray Sawyer in his contribution—a phenomenon which in the extreme case leads to pion condensation.(39,40) Or perhaps the nucleons dissociate into quarks, increasing the number of degrees of freedom per baryon at the expense of confinement energy.(41)

It should be remarked that a great deal of work has gone into particle-coincidence methods of determining the size of the region from which pions and protons are emitted. This can, in principle, be done by investigating the quantal interference of pions or nucleons, which shows up as two-particle correlations at a relative wave number which is the reciprocal of the size of the region over which they are emitted.(42-44) The quantitative application of these ideas is plagued by unresolved theoretical and experimental difficulties, but they could in principle lead to a determination of the density at which collisions cease which, together with the temperatures determined from the momentum distributions, could provide an independent confirmation of the phase-space density measured by the deuterons. Further results are awaited eagerly.

6. Concluding remarks

The above discussion has been a mere sampling of the work that has been done in the field of high energy heavy ions. It is a biased presentation with a polemic intent and viewpoint: the aim has been to show to workers in related fields why so many physicists think that these hard problems are interesting. No doubt many important data and calculations have been omitted because their importance has not yet been understood well enough so that the author is able to explain it easily to a non-expert. Apologies are due to many workers who may justly feel neglected. They can be sure that subsequent development of a better understanding of these reactions will reveal the importance of their work.

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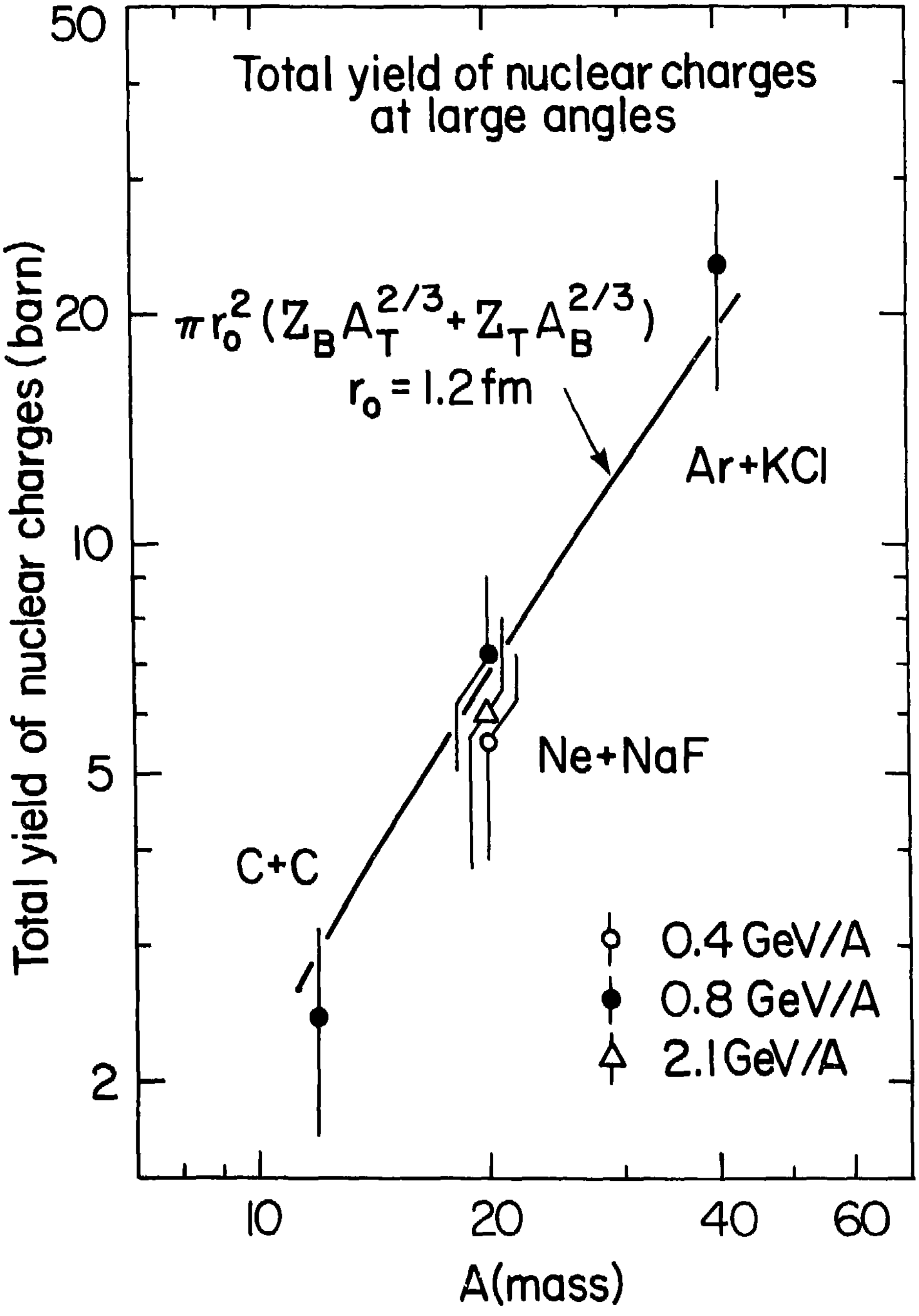


XBL 797 - 2084

Fig. 1

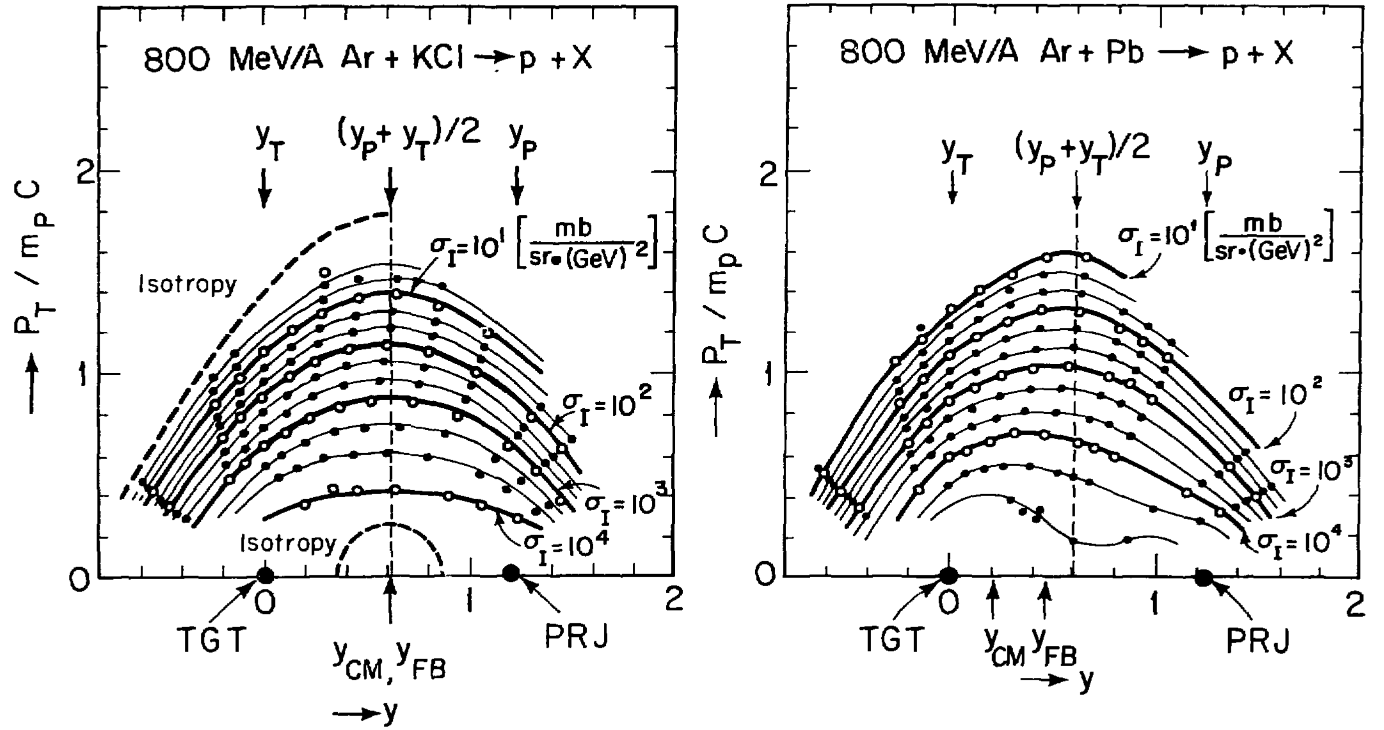
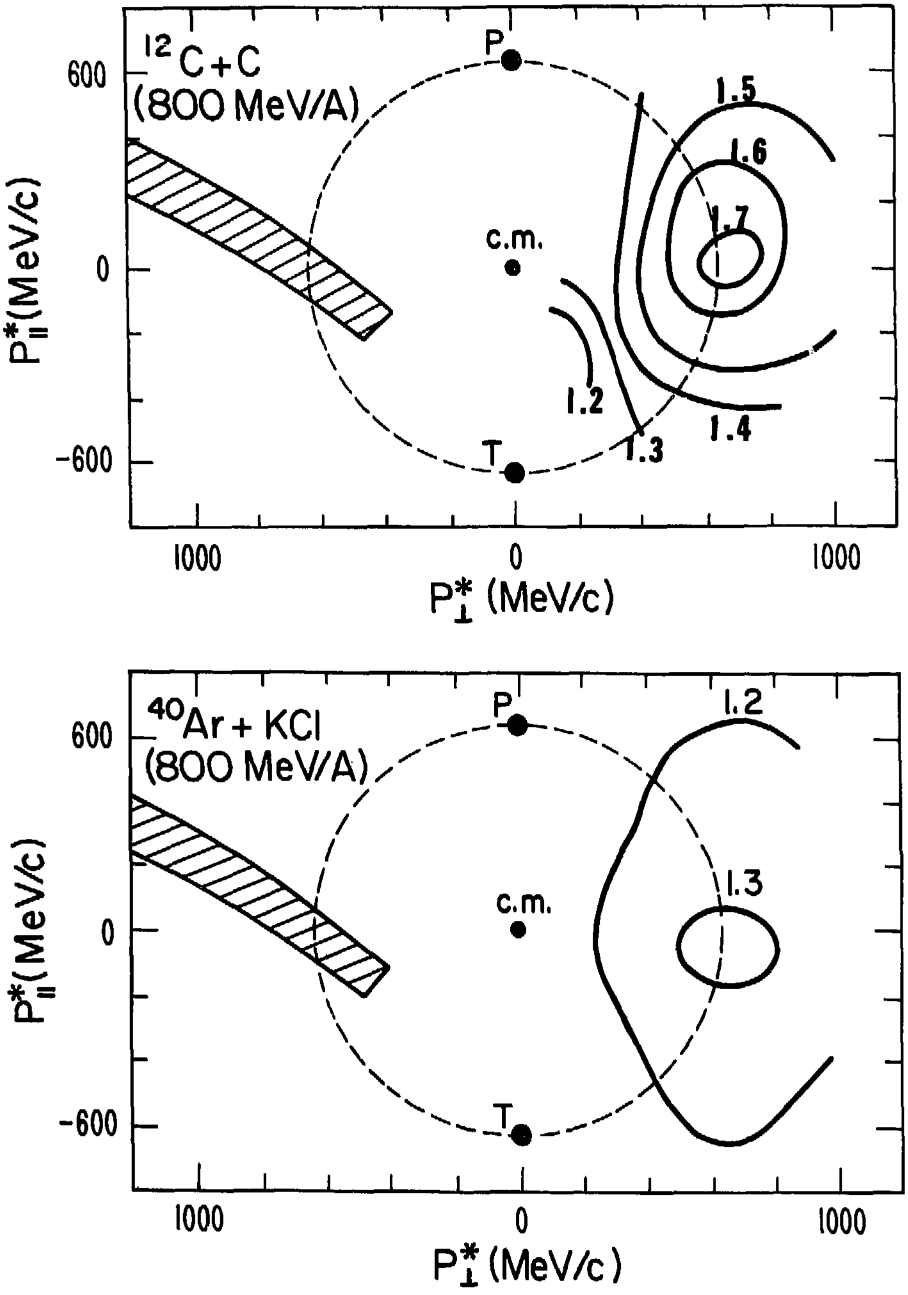


Fig. 2

XBL788-1501A



XBL 793-761A

Fig. 3

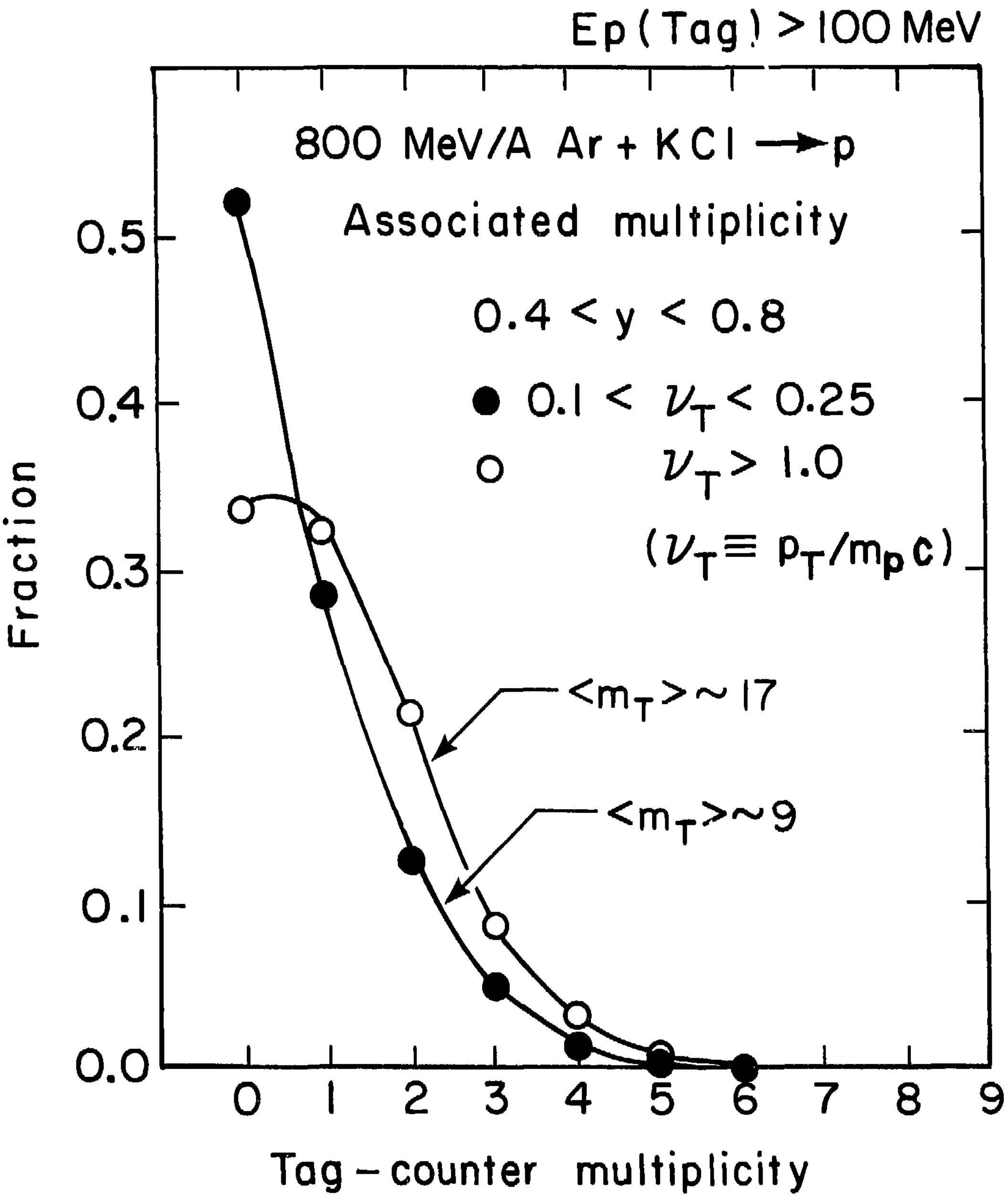
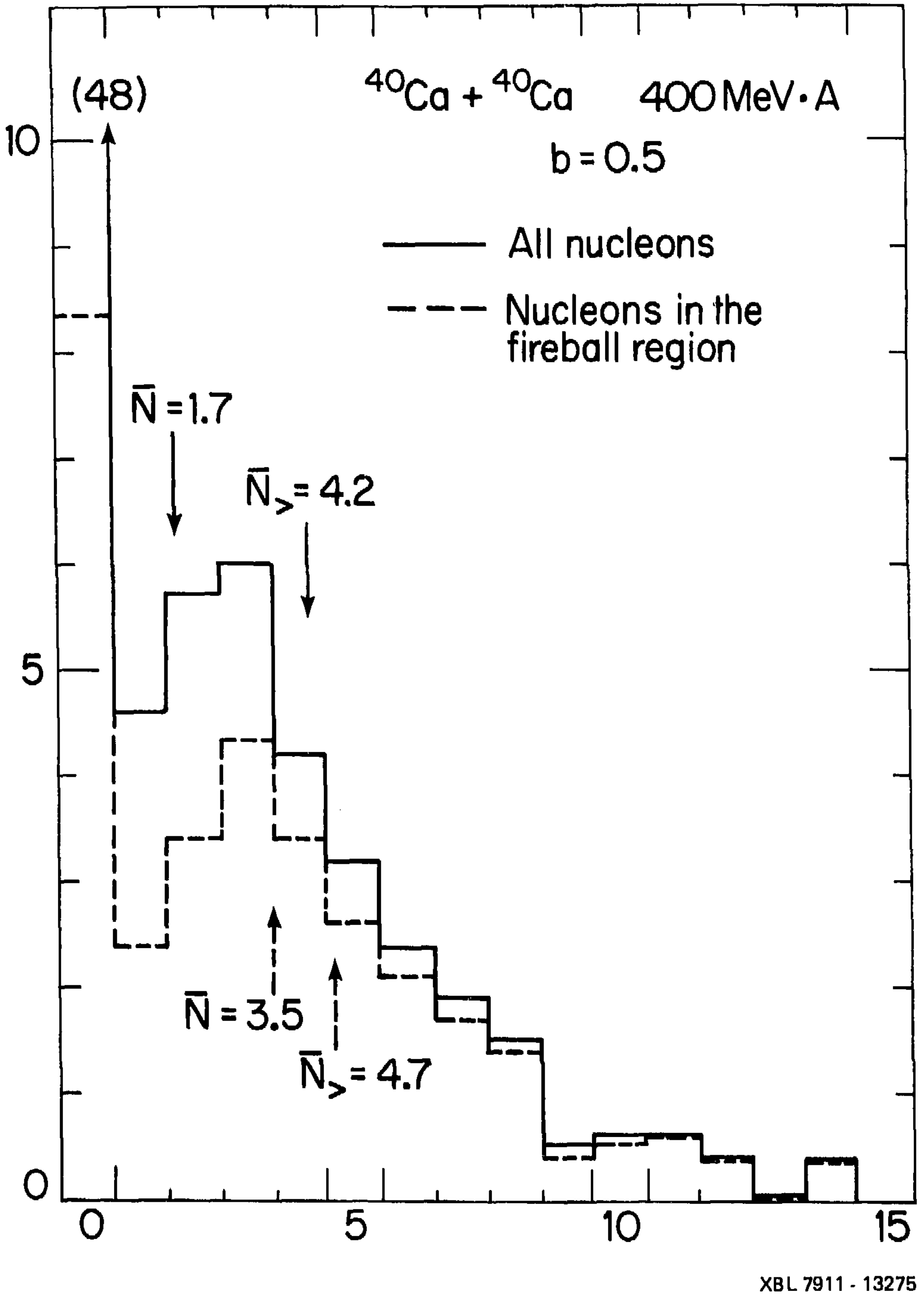


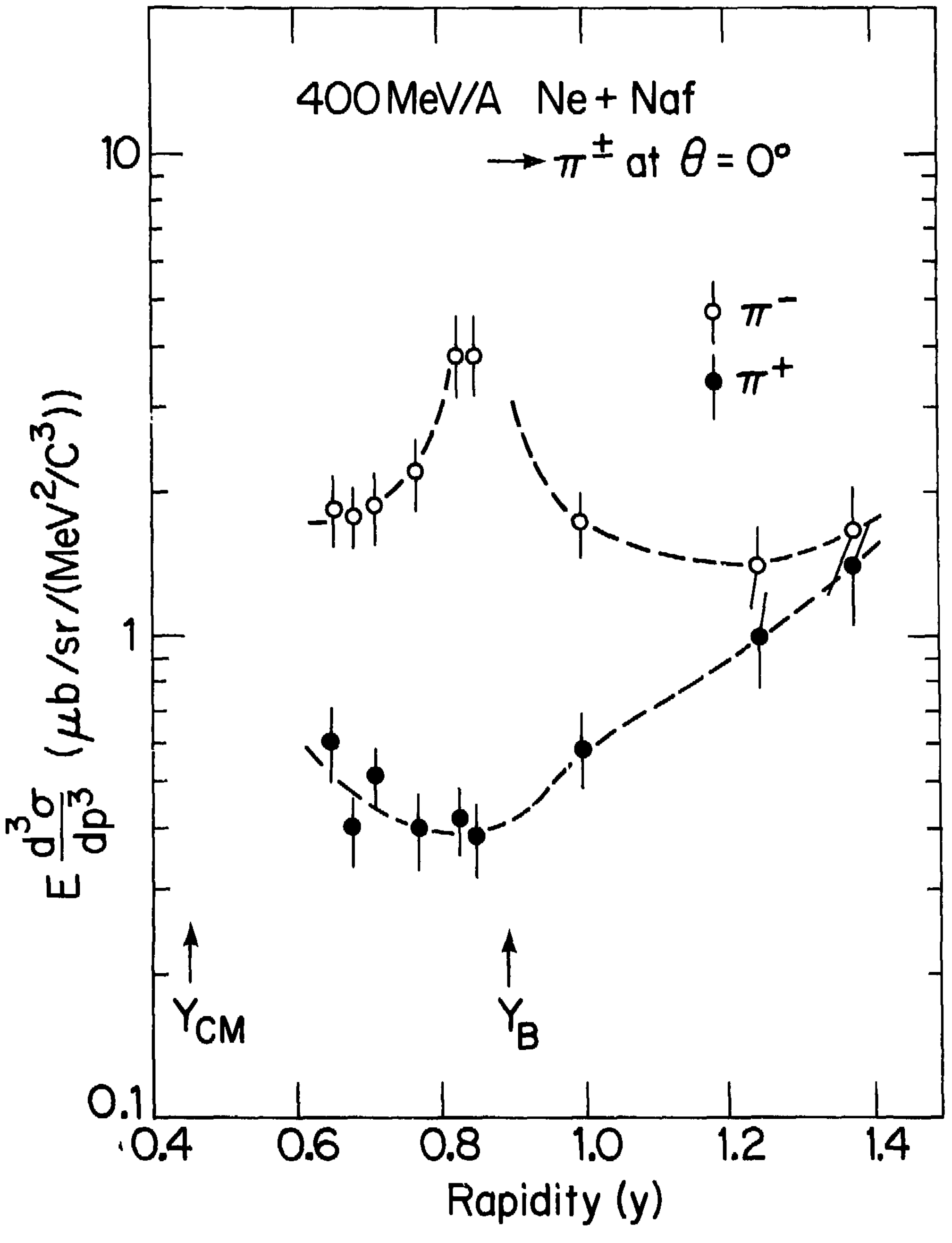
Fig. 4

XBL 7810-6626A



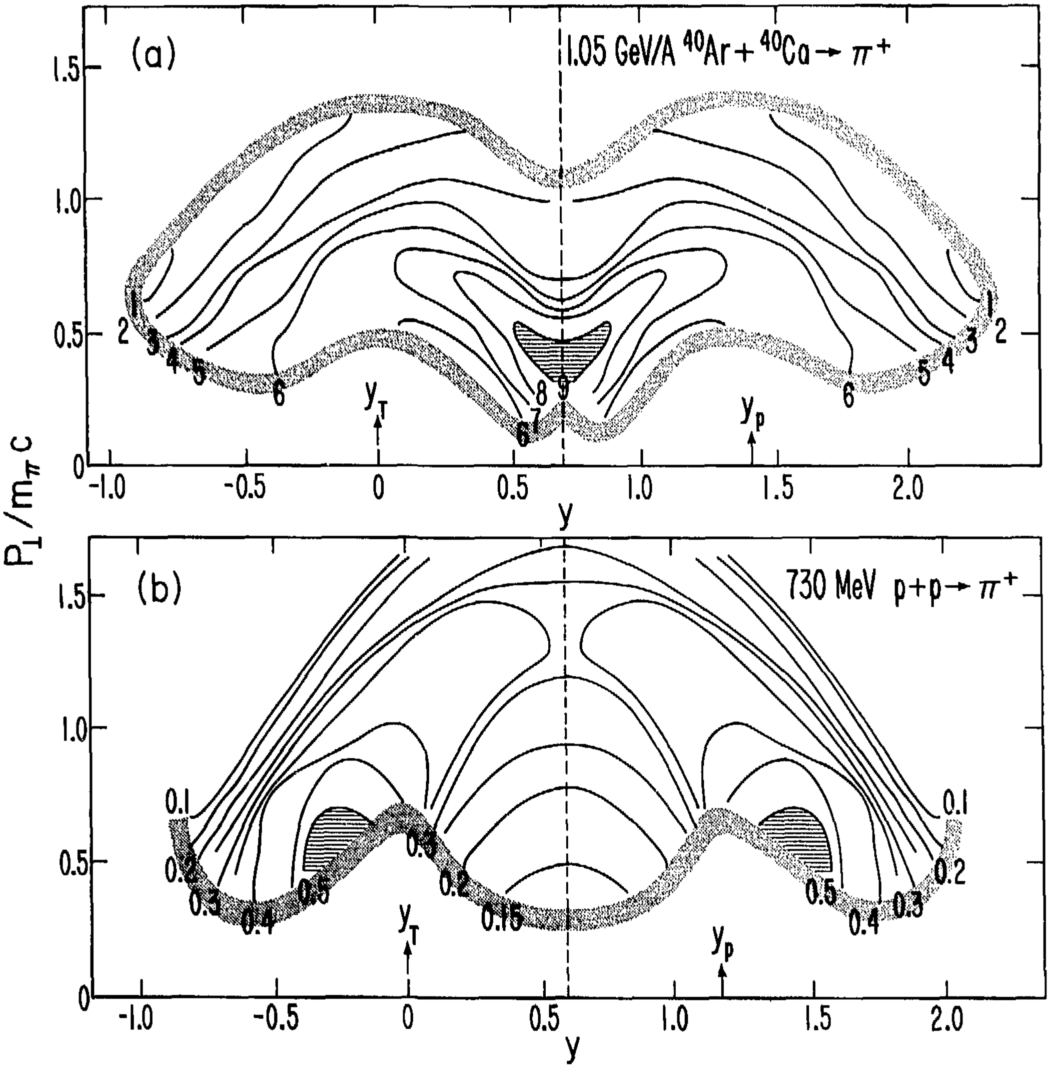
^{40}Ca + ^{40}Ca 400 MeV·A
b = 0.5
All nucleons
Nucleons in the fireball region
(48)
$\bar{N}$ = 1.7
$\bar{N}_>$ = 4.2
$\bar{N}$ = 3.5
$\bar{N}_>$ = 4.7
0
5
10
15
XBL 7911 - 13275

Fig. 5



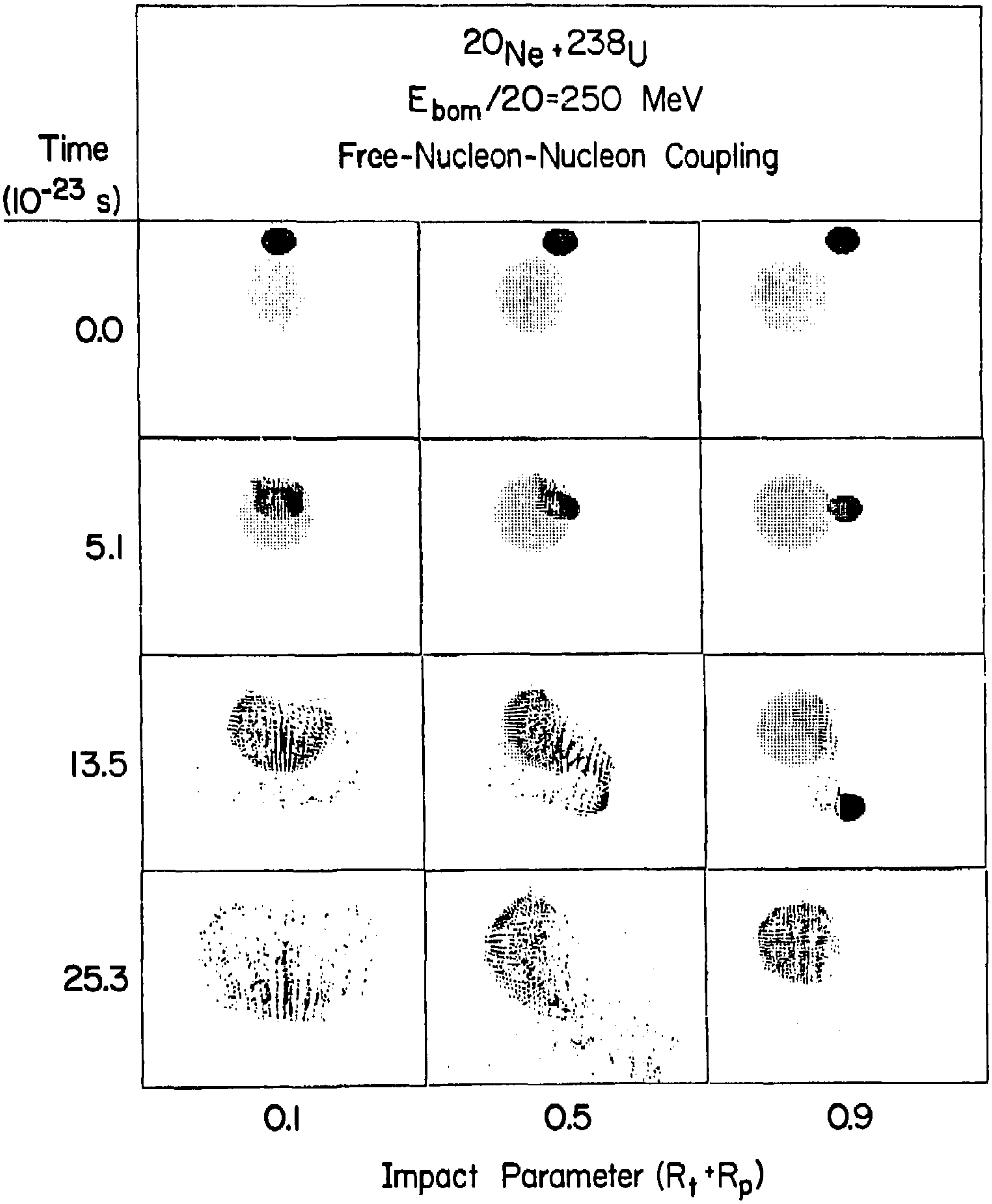
XBL 7911-13274

Fig. 6



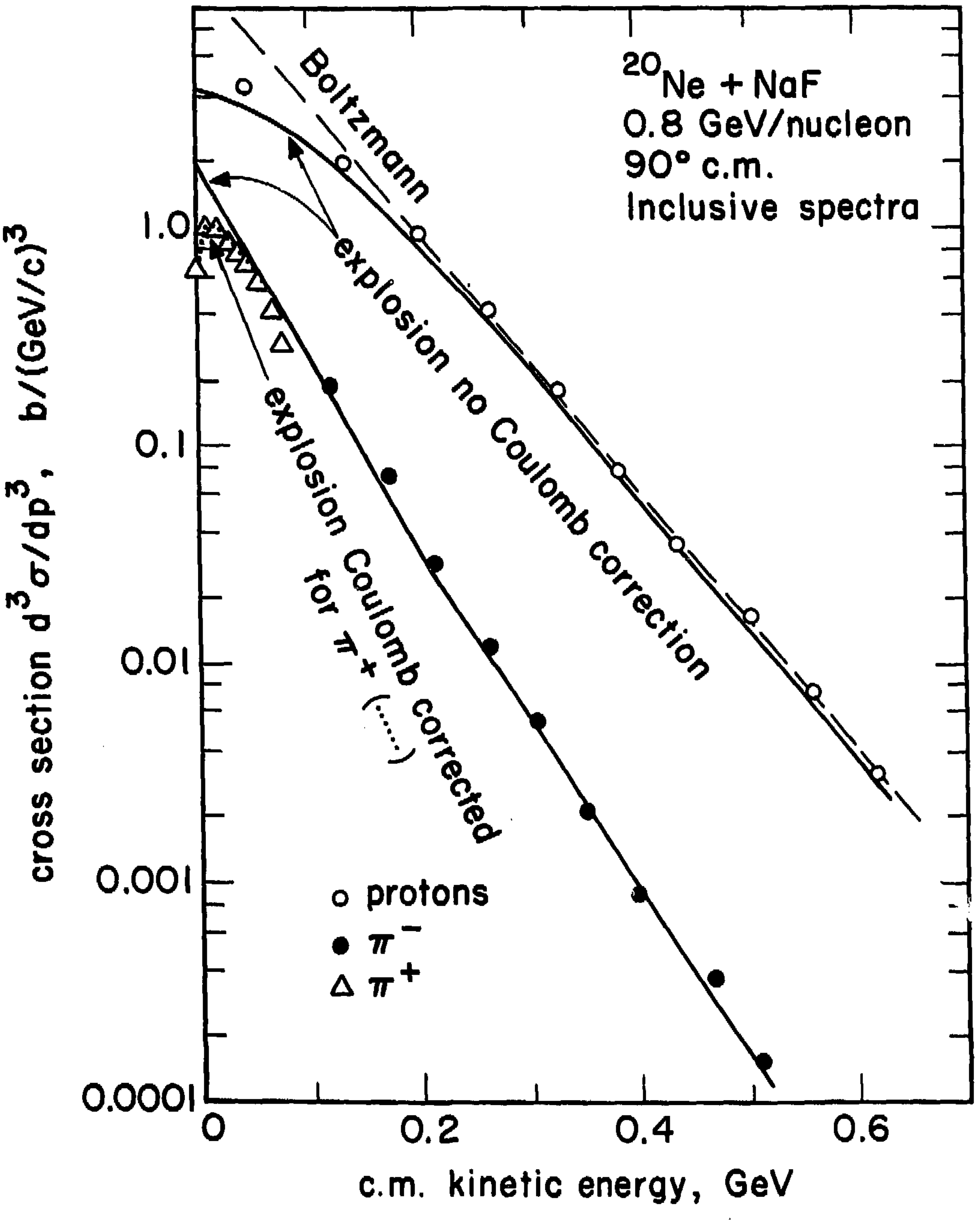
XBL 791-260

Fig. 7



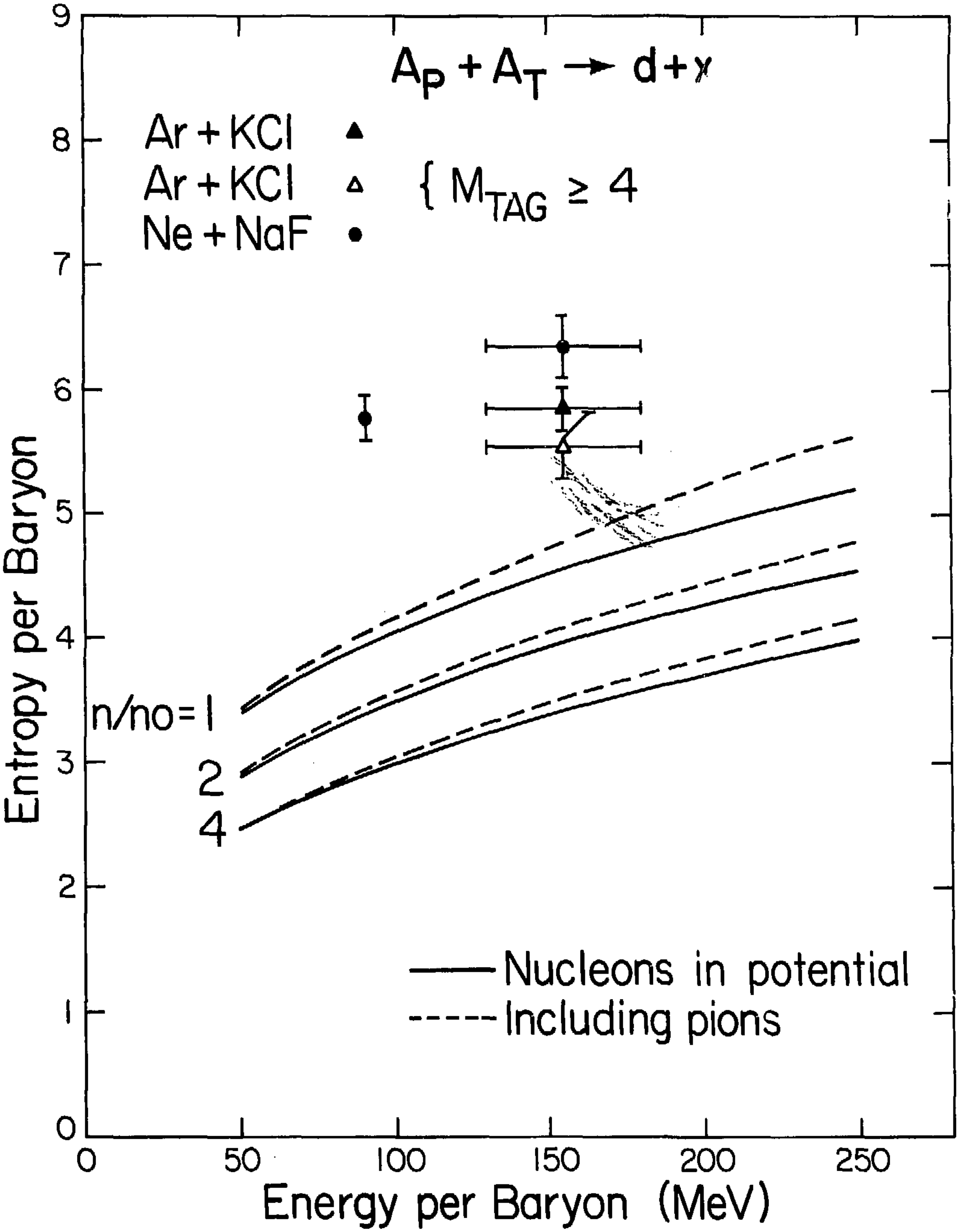
XBL 775-8770

Fig. 8



XBL 7811-12982

Fig. 9



XBL 797-2100

Fig. 10