NUCLEAR BEAMS AND TARGETS

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The work carried out in our study was more narrow than that covered by the title, concentrating on the physics of high-energy density over large volumes. This did not reflect our judgement that these subjects were not interesting, but that most of them received attention elsewhere in the Workshop. For example, the power of charged leptons as probes of the structure of nuclei was demonstrated 30 years ago by Hofstadter, and this tradition was continued at the workshop with considerable emphasis on the interesting effects seen in deep inelastic muon and neutrino interactions, but this subject was studied in other groups than ours. These effects include the investigation of constituent propagation in nuclear matter, and the unexpected discovery of form factors which differ substantially between nucleons and nuclei. We did not much discuss the "anomalous" A-dependence of high-p_T particle production, discovered by Cronin and co-workers. This effect may just be due to multiple scattering in the nucleus, but something more interesting might be involved. We did recognize that some of the experimental set-ups we discussed could be used to investigate the system recoiling against the high-p_T particle, which is the next step necessary to resolve this question.

Naturally, in our discussions of the means for attaining large and extended energy deposition we devoted much attention to the possibilities which would follow from the acceleration of ^{16}O in the PS-SPS accelerator complex$^{1)}$. The heart of the matter is the following pair of questions:

I) Is there a reasonable cross-section for events with a *large thermalized* energy deposition?

II) What are the best ways to *characterize* such events and what are the *diagnostics measurements* to derive information about the fundamental physics?

On the first question, it is now agreed to be best to start with some *experimental facts,* and base predictions for nucleus-nucleus events on these:

1. Large cross-sections for events with large transverse energy ($E_T = \Sigma E_i \sin \theta_i$) are observed in pp collisions at the SPS, ISR, and SPS collider energies. Some of these have a two-jet structure, but many have no obvious structure, particularly at SPS energies. It has been argued that these events in pp collisions may already display some features of thermalization$^{2)}$ though this is not yet established.

2. Even larger cross-sections for high-E_T events have been found in FNAL experiment E-557 $^{3)}$, where the cross-section for $E_T \sim 20$ GeV is more than 10^4 times larger in lead than in hydrogen. In Fig. 1, these results are shown. It should be noted that the E_T is integrated over only the two central units of rapidity in the proton-proton frame, and may underestimate the nuclear deposit. This need not represent any new physics in the nucleus$^{4)}$, but it is a useful check on our extrapolation to nucleus-nucleus collisions.

3. The information on nucleus-nucleus collisions is limited to a handful of events obtained in cosmic rays. One of the main current efforts is that of the JACEE Collaboration$^{5)}$. A summary of their events is shown in Fig. 2. Their scanning threshold is somewhat higher than SPS energy. These events were obtained in an "emulsion chamber": target emulsions and

lead plates interleaved with emulsions forming a photon calorimeter which allows energy measurement, all flown in a balloon. One of the most interesting events is a collision of Si with Ag, yielding a particle distribution in pseudorapidity ($\eta = -\ln \tan \theta/2$) shown in Fig. 3.

The event is estimated to have an energy of about 4 TeV•A. The number of charged particles per rapidity interval is about 200, for a total of about 1000. We may suppose E_T is of the order of 500 GeV. It is particularly noteworthy that the distribution shows no depression at mid-rapidities, contrary to some theoretical speculations. Since this event represents one of a sample of only a few, and the scan is not highly biased, it is evident that the cross-section in such reactions for very high E_T events must be very large indeed. Of course, we can have little information from these experiments on the fluctuations, for example, those which give E_T several times the average value. These might be accessible with accelerator experiments.

Recently the data from the JACEE events have been analysed by Gyulassy and Satz6) to give direct estimates of energy densities in the interaction volume in the early stages of these collisions. The resulting values are in the range 1-2 GeV/fm^3 (Fig. 4), an order of magnitude higher than the energy density in a nucleus and large enough to ensure that the matter should be above the phase transition from hadron gas to a quark-gluon plasma, as discussed in detail by Satz in these Proceedings6). Another calculation of the energy density was presented to the Workshop by Danos and Rafelski7), and included the effect of hadron radiation from the surface of the interaction volume. They found a rather rapid dependence on the energy of the colliding particles, as shown in Fig. 5.

Our understanding of the energy density question has progressed quite a bit in the last year or two, thanks to the work of Anishetty, Koehler and McLerran8), Bjorken9) and others, as well as the authors of Ref. 6. The question which needs more study is to which degree the deposited energy becomes equilibrated and is thermalized. The relativistic statistical mechanics of this process are explained by Van Hove in these proceedings10), and rough numerical criteria for thermalization are given by Satz6), which seem quite encouraging. Only inspection of experimental data can carry us much further in this direction.

Indeed, it seems that it may not be possible to discuss quantitatively the sensitivity of the different signals proposed for the observation of the hadron-quark phase transition until we have some information on how accurately we can characterize these systems, including the degree of thermalization. It is therefore impossible to state in advance the amount of effort required to demonstrate this phase transition, though as Van Hove pointed out, if there is really a first order transition with as large a latent heat as calculations suggest, it may show up in a clear way11).

Turning then to Question II, a number of measurements have been suggested for *characterizing* the high energy-density matter:

1. Total value of E_T, by calorimeter measurement, used in all probability in the trigger to select events with high E_T.
2. Spherical symmetry, by distribution of $dE_T/d\eta$. Truly thermalized systems should display this symmetry, though local equilibrium in a co-moving system may suffice for many purposes10). It may be desirable to include this condition as a calorimeter trigger requirement.

3. Net baryon number, by proton identification and neutron energy fraction. This may account for a large fraction of the energy, as in the target fragmentation region, or may be relatively small in an event where most of the energy appears in the "central" region. Increasing this fraction for fixed energy should carry the system through the phase transition, which makes this a vital and interesting parameter to control.

4. "Temperature profiles", by measurement of the energy spectra of hadrons, photons, and leptons. In any collision, leading to a thermalized system, temperature should fall with time. The fact that low-energy hadrons can be described by almost constant temperatures has long attracted notice. Now that we know that this temperature is close to that of the hadron-quark transitions$^{6)}$, we might identify it with matter kept at that temperature for a time by the latent heat of the transition. The photons and leptons should read mainly the higher temperature of the earlier stages of the collisions, and perhaps they do, even in hadron collisions$^{2)}$. These studies will be of paramount importance, and we may say that nucleus-nucleus experiments will be above all lepton-pair experiments. At the same time, it seems necessary that all the other elements of the characterization should be available, which means that the experiments must combine lepton-pair measurements with a powerful "open" spectrometer, a difficult requirement.

5. Volume, by identical particle intensity interferometry and perhaps deuteron/proton ratios. A "direct" measurement of the volume will be most useful to give some check on estimates of energy density, when combined with E_T. Identical particle interferometry has been tried many times, with the result that one has learned that it is a difficult technique. It must be noted that it relies on finding more than one particle in a relatively small cell of phase space, so that the power increases rapidly with the multiplicity in the event, and consequently is much more appropriate to the present case. It has also been shown that the technique can be applied to proton pairs, and to determination of the volume and shapes of sources which are not spherical$^{12)}$ as shown in Fig. 5. When the density of pions, for example, is such that an appreciable fraction of the whole is affected by interference, the usual technique of computing two- and three-particle correlations becomes inappropriate from the standpoint of statistical analysis, and it is better to use the techniques developed for "classical" fields, such as the autocorrelation function used in speckle interferometry.

   The probability for a neutron and a proton to form a deuteron is related to the spatial density in which the nucleons are confined, and certainly is a relevant number to measure, though the different aspects of deuteron production are still controversial$^{13)}$.

   The volume measurements which depend on hadrons can only measure the surface at which the hadrons are formed or last interact. Information about the volume during the early stage of the interaction would seem to have to come from observations on the electromagnetic particles. If it is true that directly produced photons become comparable to photons from π^0's, particularly in the case of the somewhat higher energy photons radiated at the early stages of the collision$^{14)}$, it might be possible to make interference measurements using those; otherwise, models must be used to connect the volume measured by hadron to that responsible for the real and virtual photon emission. In order to check these models, and more generally to allow the separations of surface and volume effects, it is important to compare collisions with all the parameters the same except the volume.

6. Quantum number composition, by charged-particle identification and neutral V^0 reconstruction, to give the fractions of pions, baryons and antibaryons, strange particles, and perhaps even charmed particles, which can give characteristic results concerning the Fermi sea of quarks, *if* such effects survive the final hadronization.
7. Clustering, in phase space. This occurs owing to identical particle interference, but on a very tiny scale. Clustering on a larger scale is a well-known but not well-understood effect in proton-proton collisions. It is not just related to resonance production, since it is observable as well in clusters with "exotic" quantum numbers. It may have much to tell us in high-E_T events.

If some program has been made in attempting to characterize events along these lines, it should be possible to make quantitative estimates on signals of phase transition, which appear as specified patterns in the parameters determined in the characterization. For example, it has been stressed that the quark plasma just above transition contains anomalously few $\bar{u}$ quarks and anomalously many s quarks15). Whether this leads to anomalously few antibaryons and anomalously many strange baryons involves questions of surface behaviour which probably can only be resolved by experiment.

The clustering effects mentioned above could be striking in nucleus-nucleus events, and a sign of a domain structure associated with the phase transitions11).

The tool which would be best in principle as a signal for a phase transition would be the lepton-pair production. Several effects may be studied. If all other parameters were fixed, the radiation law would give the number of types of charged particles participating in the radiations. This would increase strikingly as the energy density was increased above the transition. Since the actual observation integrates over time and temperature, the observation is not a simple one, but it seems that it ought to be possible if the event characterization is sharp enough16). Another effect which has been suggested is the shift in the mass of the ρ-meson immersed in the quark-gluon plasma and observed by its two-lepton decay17). If the energy density is high enough, there will be a "melting" of the mesonic structures, and the ρ, ω, etc., observed by leptonic decays, will simply disappear. Here we refer to the volume productions, showing again the importance of the measurement and separation of the surface and volume components.

We discussed the experiments necessary to do these measurements using the extensive work done in the Workshop of May 1982 in Bielefeld18). The studies had advanced considerably in the intervening time. We heard descriptions of two experiments on inclusive lepton-pair production, adapted from existing SPS experiments. One, based on the NA3 experiment, concentrates on the Feynman x_F region near zero in the nucleon-nucleon frame19). Figure 6 shows the result anticipated for a thermal quark-gluon plasma, compared with a "background" from proton-nucleus collisions measured in the same apparatus and scaled linearly with the number of nucleons in the beam. The "background" in the region of the thermal peak is due in large part to the narrow ω and ϕ resonances which could in principle be removed, but the curve reflects the resolutions of this type of experiment, with severe scattering in the muon absorber. The "signal" to "background" also reflects the region in x_F chosen. As shown in Fig. 7, this region is at the peak of the "background", while the thermal radiation is expected to peak at smaller rapidities, for heavy targets. Nevertheless, it is very encouraging to see that an existing apparatus ought to see the presence of the thermal radiation in a few days run.

In Fig. 8 it will be seen that the "signal" to "background" ratio becomes favourable for large x_F, where the nucleon cross-sections must vanish at $x_F = 1$. Another group has considered the use of a slightly modified NA10 apparatus to measure in this region$^{20)}$. The excellent x_F resolution of this experiment should allow a very clean result, as shown in Fig. 8.

Another group studied the use of an apparatus which does not now exist at the SPS, but which was put forward in another part of the Workshop as a tool for lepton and lepton-pair studies, the Spherical Field Spectrometer (SFS), shown in Fig. 9. This is a compact open spectrometer intended to retain good lepton-pair resolution over the whole rapidity range$^{21)}$. The results of Fig. 7 already suggest the importance of a wide angular coverage, but those curves are estimated for the average over all interactions. One of the advantages of the SPS for this programme is that one is free to choose a very heavy target, and trigger on a small fraction of events when E_T is much larger than the average. In this case, kinematics tend to force the system with the large energy deposit to fall at small laboratory rapidity, and of course the lepton pairs from thermal radiation will be found at nearby rapidities. The calorimeter in the SFS can be used to trigger on the events of interest. It is beyond our ability to calculate the cross-section for such fluctuations, but we choose a "typical" event which might result from such a trigger. It has 200 GeV of excitation energy deposited in a target of effective nucleon number 130, a similar number per incident nucleon to the cosmic-ray event shown in Fig. 3, and about one third that allowed by kinematics for a ^{16}O beam of 200·A GeV. The peak of the energy deposit is then at $\eta = 1.0$. We assume that the remaining beam energy is deposited in the manner typical of nucleon collisions, while the thermalized excitation energy is dissipated isotropically in its rest frame. This gives rise to the energy (measured with calorimeter) as a function of pseudorapidity shown in Fig. 10. We assume that the thermal energy is equally partitioned between pions and protons, with an average kinetic energy of 400 MeV. Then there will be 300 pions and 130 nucleons in the final state of this system, and the distribution of all particles (counting a π^0 as two particles) is shown in Fig. 11. For this kind of event, the "background" of lepton pairs from ordinary nucleon-nucleon collisions is negligible in the region of the thermal peak. Some thought has been given to use this spectrometer for the measurements necessary to characterize the events in the way described above, as well as trigger on high E_T and measure the lepton pairs$^{21)}$.

A group studied the use of the Ω' spectrometer with nuclear beams and targets$^{22)}$. They emphasized the symmetrical reactions ^{16}O-^{16}O rather than the use of heavy targets. The Ω' is then more suited because the reaction products are found in the forward direction, with the same distributions as for hadron-hadron interactions. Such reactions are probably the best way to study the central rapidity region to obtain the high-energy density events with the lowest fraction of baryons. The Ring Imaging Cherenkov (RICH) counter which is being constructed for Ω' will have very good multiple particle separation as well as particle identification. It is thought that with an ^{16}O target, the charged-particle multiplicities should be within the range which can be handled by the present spectrometer, especially with the aid of special triggers to select events which fluctuated in the direction of neutral particles.

A programme of a rather different nature was also foreseen, on the forward fragmentation of possible ^{4}He beams to study multiple baryon states. A small new forward detector would be added to supplement the existing spectrometer for this purpose. Also, the spectrometer would be triggered on high-p_T particles and the recoil jets analysed to examine the question of the origin of the anomalous high-p_T enhancement.

The question of experiments on "anomalons" was naturally raised. This refers to the emulsion observations at the Bevalac and in cosmic rays of heavy secondary nuclei from nucleus-nucleus interactions with anomalously large interaction cross-sections, as shown in Fig. 12. It is not quite obvious how to do this experiment at SPS energies. At $\sim$ 3 GeV/c•A, the emulsion experiments found that the secondary tracks emerged from the region of confusion in the forward cone after about 1 mm (this in a detector with about 1 μm resolution). At 200 GeV/c•A, Lorentz scaling would indicate that the confusion would persist for about 60 mm, probably obscuring the observed effect. One suggestion for an arrangement to avoid this problem was a thin emulsion target, a 100 mm gap for the tracks to separate in space, and an emulsion stack to observe the secondary interactions[23]. The holographic bubble chamber in EHS was also considered as a possible solution to the resolution problem, but no detailed studies have been made.

Another idea was to use a thin internal target in the SPS during acceleration, particularly convenient for measuring the excitation function of inclusive spectra, simultaneously on a number of targets of different A mounted as fibres on a spinning wheel, for example[24].

The two detectors which have been proposed for the PS experiment are a streamer chamber and the Plastic Ball, a complete coverage calorimeter for low-energy particles[1]. We discussed their application to SPS energies and concluded tentatively that interesting results could certainly be obtained with these detectors at the SPS, particularly at the lower end of the SPS energy range, but the experimenters presented convincing arguments for the experiments they proposed at PS energies, and showed that their detectors were really optimized for that energy.

Finally, in view of the detailed information provided now by nuclear emulsions on the cosmic-ray events, and their unique spatial resolution which allows one to deal with extremely high particle multiplicities, we should not forget that there are a number of active emulsion groups who are very eager to obtain exposures to high energy beams, and who are sure to produce interesting results.

In summary, substantial progress has been made in understanding events with high-energy deposition. An outline exists for connecting them with otherwise inaccessible areas in non-perturbative QCD and the state of matter in the early universe. Experimenters exist who are eager to try to use existing equipment at the SPS to provide much-needed experimental data.

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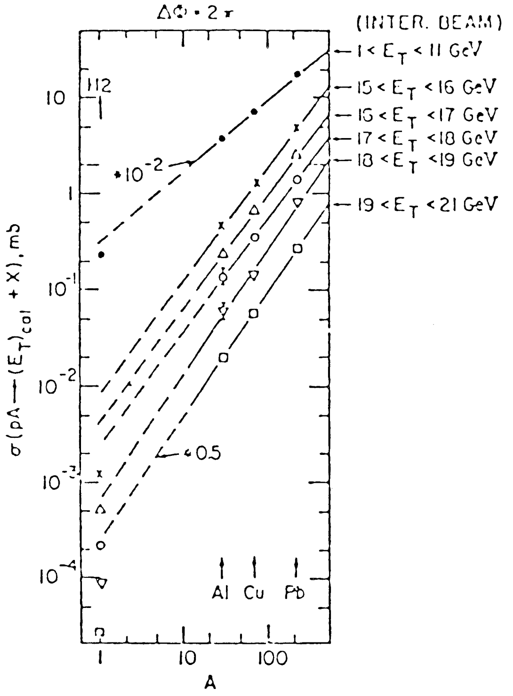

Fig. 1 The E_T spectrum for proton-A collisions for 400 GeV protons, from FNAL experiment T-557 (see Ref. 3). Note that E_T is integrated only over $-1 \lesssim \eta \lesssim 1$ in the nucleon-nucleon centre of mass.

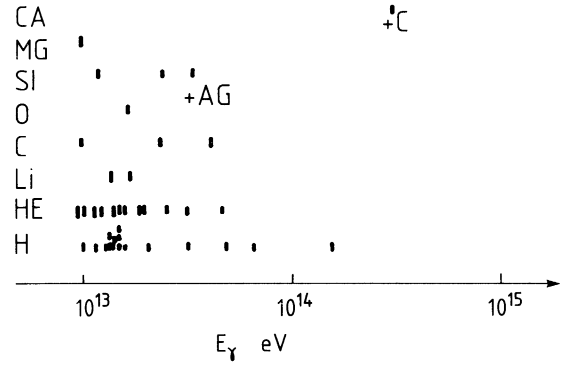

Fig. 2 A summary of the cosmic-ray events studied by the JACEE Collaboration (Ref. 5).

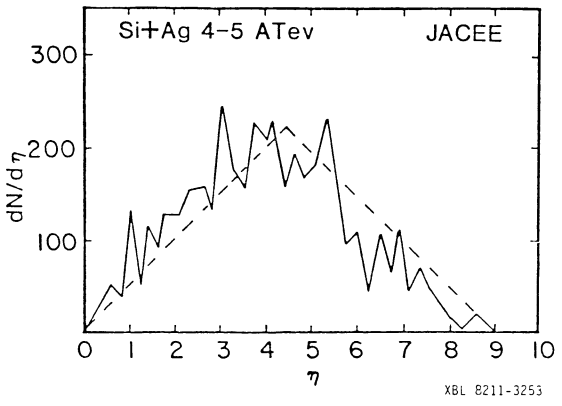

Fig. 3 A plot of the particle distribution in pseudorapidity in an event of Si + Ag from the JACEE Collaboration.

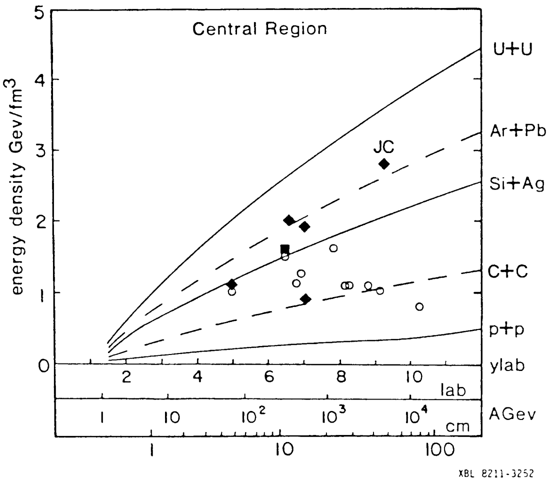

Fig. 4 Estimated values of the deposited energy density in the JACEE events, from Ref. 6.

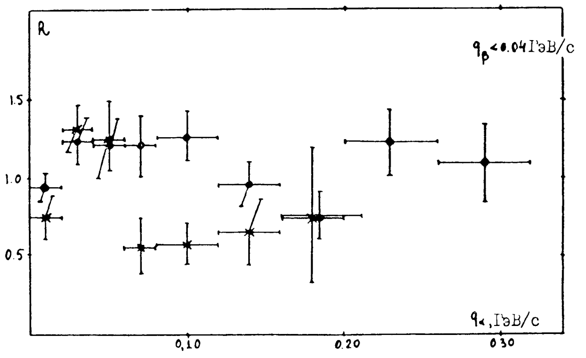

Fig. 5 Correlation function for two protons from proton-lead collisions at 10 GeV, as a function of their relative momenta in a plane containing the beam (dots) and in the orthogonal plane (crosses), showing evidence for identical particle interference effects from a non-spherical source (Ref. 12).

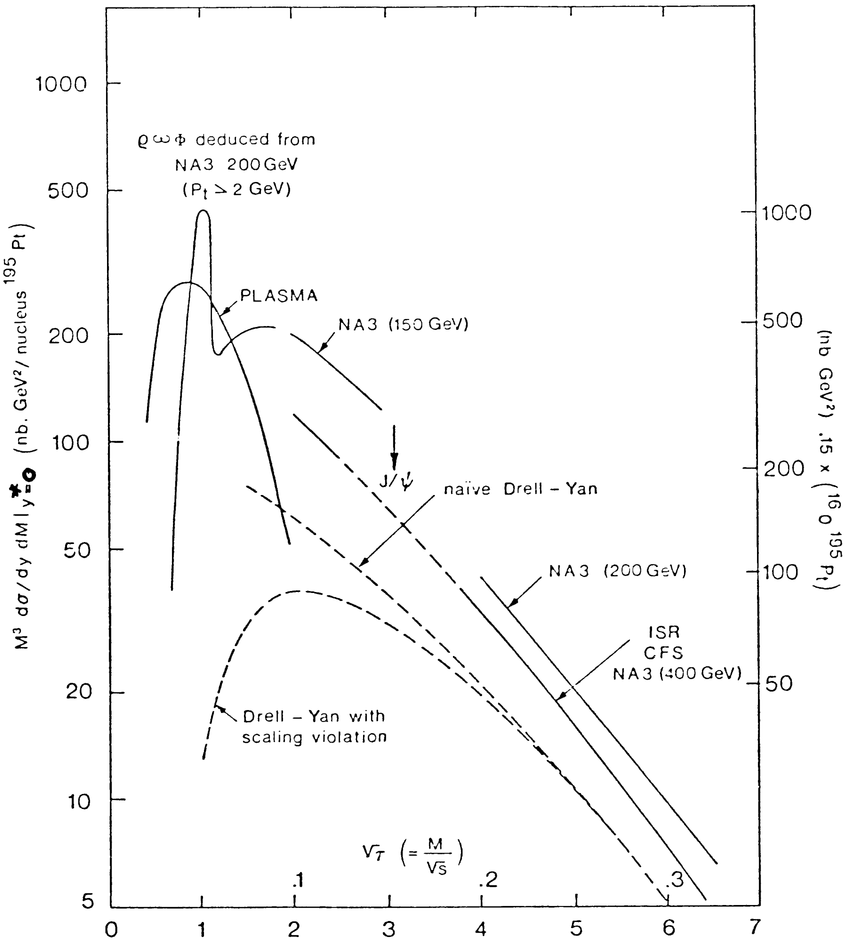

Fig. 6 The cross-section for thermal radiation of lepton pairs from a quark-gluon plasma compared with a scaling to nuclear beams of the NA3 results on proton-nucleus reactions at $x_F = 0$ (Ref. 16). Note that the ρ, ω, and φ are merged into one broad peak by experimental resolution.

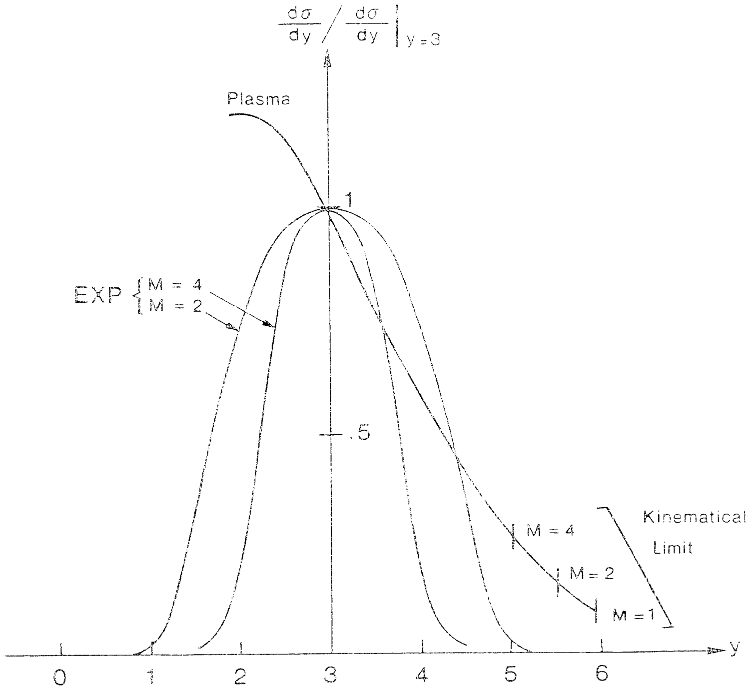

Fig. 7 The expected value of the thermal radiation of lepton pairs by a quark-gluon plasma in the average ^{16}O-^{208}Pb events, compared with that scaled from nucleon-nucleon collisions, versus Feynman x_F (Ref. 16 and 19).

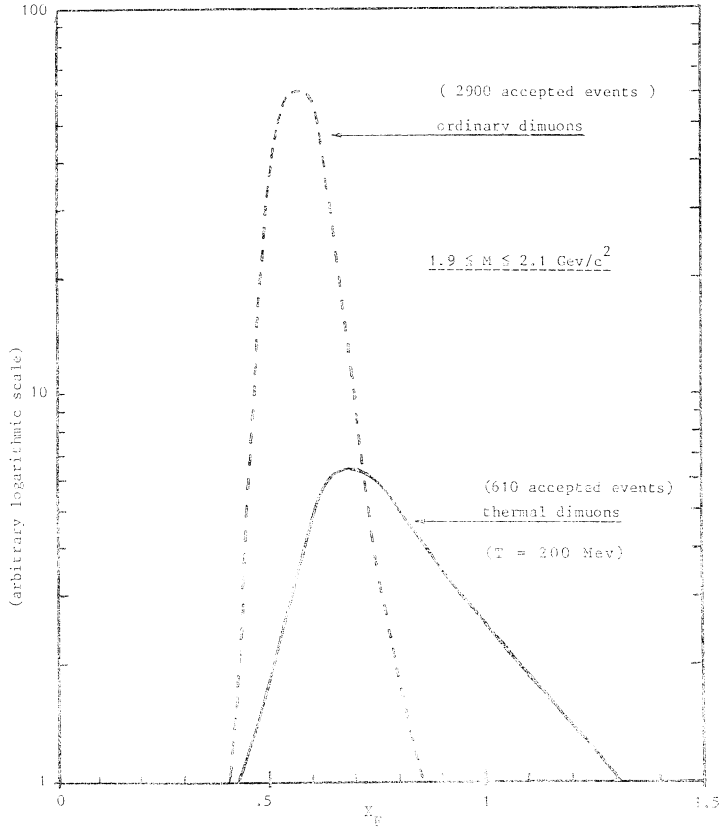

Fig. 8 The anticipated distribution of numbers of events as a function of x_F for lepton pairs from a thermal source compared with those from scaled nucleon-nucleon interactions, for the modified NA10 apparatus with a 10-day run (Ref. 20).

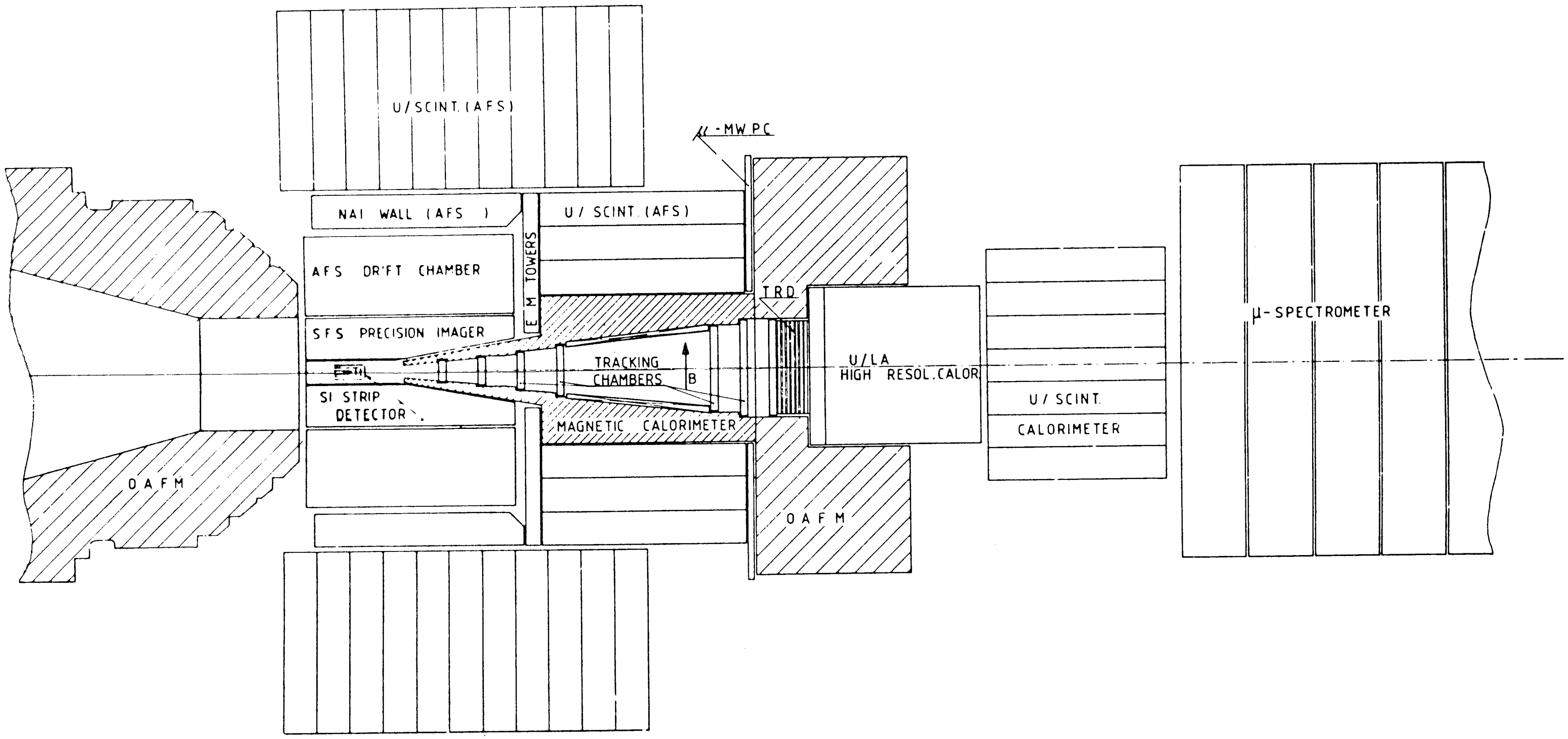

Fig. 9 Plan view of the proposed Spherical Field Spectrometer (Ref. 21).

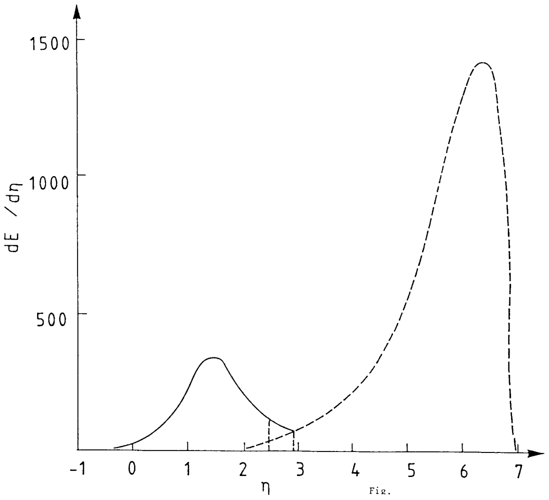

Fig. 10 Distribution of energy measured in the calorimeter as a function of pseudo-rapidity η for a "typical" ^{16}O-heavy target event triggered on high E_T (Ref. 21).

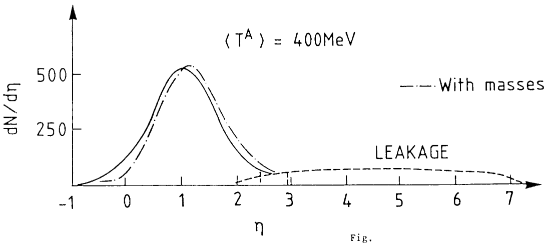

Fig. 11 Distribution in η of the number of all particles, charged and neutral, for the "typical" triggered event of the previous figure.

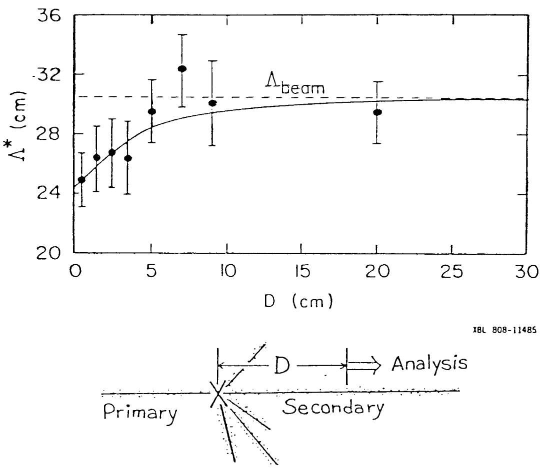

Fig. 12 The distribution of distance between the creation and interaction of secondary nuclei: the evidence for the Bevalac "anomalons" (Ref. 23).

DISCUSSION

A. de Rújula: Could you show the transparency that was dedicated to a question yesterday on radiation? What is the size of the nuclei in there?

W. Willis: I believe it is two rather heavy nuclei, but I will have to check the paper. I think it is uranium against uranium.

A. de Rújula: So that probably matters. Now, what would the effect be of assuming no radiation?

W. Willis: Well, no radiation will be a curve you can sort of guess - it is something like that...

A. de Rújula: So, it makes a big difference.

W. Willis: Yes. Your question is well taken. Of course, this is not a rigourous calculation of the radiation - it just assumes that quarks are banging against the side of their volume and once in a while they go through. So you may deny or believe it, but it shows that on dimensional grounds radiation can be important.

G. Coignet: I have one remark on your first transparency. You said that with the lepton beam you can study the nuclei, and just afterwards you said that hadron propagation in nuclei is something interesting and that the details have still not been settled. So I will just remind you that there is one way to study that sort of thing, and that is precisely to use lepton beam where you produce one virtual photon. If x Bjorken is not too small you hit a quark and depending on the energy you transfer you can see if it is quark or hadron propagation. The main advantage of the lepton beam is that you have no interaction in the initial state.

W. Willis: Yes, that sounds very correct.

NN: I have one question about interferometry. If you make these analysis and if you find out that for example the radius of this source is 1 Fermi instead of 5 Fermi, how can you interpret that? How can you make sure that it is coming from some plasma? Because it could also be that it is just an interaction of the two different pairs of nucleons in the colliding nuclei.

W. Willis: In essence you are asking me how could one determine the size of the deposit of thermalized energy, because without such determination it would be natural to assume it is multiple reaction on many nuclei?

NN: Yes ... and what is the signature of thermalization and of the occurrence of quark-gluon plasma formation?

W. Willis: Two different questions. The thermalization: the way to check if something is thermalized is to first find lots of thermometers, because if I have only one thermometer I may not trust it, but if I have ten different types of thermometers and I put them in the same bath and they all read the same temperature, then I decide they are all probably good thermometers. So, there are ways to test thermalization. Then there is the other question: what is the crucial test of quark-gluon plasma? I have not seen it. There may turn out to be one, because maybe nature is more clever than we are, but I imagine, as I said in the beginning, that you have to have fairly good understanding of quite a few aspects of this matter. However, that could be wrong, as L. Van Hove showed yesterday. If there is really a big latent heat, you might have very obvious effects, at least the one he showed. I had not seen that before and it was rather startling, the correlation of p_t with multiplicity with a funny wiggle, so you may find the funny wiggle and prove the next day that that is unambiguous, but I would hesitate to put my finger on that at the moment - it may not exist.

M. Tannenbaum: Excuse me Bill, but it seems to me that by your original arguments you have proved beyond doubt that E_t is soft, because we know from the SPS collider compared to the SPS fixed target that at a fixed value of E_t, like 10 GeV, if you go up in $\sqrt{s}$, the cross-section goes up tremendously.

W. Willis: Yes.

M. Tannenbaum: Well, you just said that the same thing happened at the SPS energy when you use a heavy nucleus in place of a proton.

W. Willis: Yes.

M. Tannenbaum: Well, for soft stuff, $\sqrt{s}$ goes up like the square root of the mass of the heavy nucleus. If the cross-section goes up, you are implying that it goes up because of the effect of $\sqrt{s}$. But $\sqrt{s}$ is only valid if it is soft, i.e. there is not much momentum transfer.

W. Willis: I fully agree with you. I also think that that curve of Bjorken, although not strictly relevant, is very suggestive.

J.P. Merlo: If I understood you, you do not make any difference between u or d quark in your nuclei.

W. Willis: I do not understand the question.

J.P. Merlo: Since you compare e.g. $\alpha\alpha$ with pp and you have different composition of protons and neutrons in terms of u or d quarks, I suppose you do not make any difference between u or d in all your deductions?

W. Willis: That is certainly true. As far as high multiplicity or high E_t events go, if you look at pp events versus $\alpha\alpha$ I do not know that there are any effects, aside from the trivial ones due to the electric charge, that you can identify as being linked to the different quarks.

F. Dydak: Suppose we live in an ideal world and you are very excited about smashing nuclei upon nuclei. Would the SPS be your preferred choice to do such an experiment? Or would you rather decide to do such an experiment on a dedicated storage ring facility, because in the end you might go to higher energies and it might be an easier experimentation to disentangle these complicated events.

W. Willis: Do you want an answer, or is it a self-answering question?

I. Mannelli: The question was put before, indeed!

W. Willis: Yes, you're doing well!

F. Dydak: Could you comment: Are there any existing storage ring facilities all over the world - I have no idea - where you could do such an experiment?

W. Willis: We can organize a search party...

I. Mannelli: You do not have to walk too far! The Intersecting Storage Rings are still here at CERN, at least for a little while....