81-10-293
高工研図書室

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP/81-120
30 September 1981

HIGH-ENERGY NUCLEUS-NUCLEUS COLLISIONS, IDEAL AND REAL EXPERIMENTS

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Talk given at the
EPS Int. Conf. on High-Energy Physics
Lisbon, 9-15 July 1981

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1. CONNECTION WITH THE QUESTION OF CONFINEMENT

In the previous talk, Prof. McLerran has discussed how collision between high-energy heavy nuclei can re-create the conditions prevailing in the early stages of our Universe. He explained our present belief that quarks and gluons are not confined under such conditions. To identify the effects of these phenomena in the transient conditions of high-energy nuclear collisions, using the techniques of high-energy physics, is the task discussed in this paper. This question has not been discussed very much, and involved a number of unusual problems, both conceptual and technical. The plan of this paper is to recapitulate briefly the basic ideas of the previous paper, show how they lead to ideal experiments, discuss some strategies for real experiments, and refer to some of the technical problems.

Quarks and gluons exist; they are nearly massless, but it is very hard or even impossible to knock them out of the proton. It is now widely believed that this strange state of affairs is due to the properties of the physical vacuum state as it now exists in our part of the Universe. On this view, the ground state of the vacuum is not that familiar in quantum electrodynamics (QED). That state is basically empty space, perturbed by fluctuations which occasionally give rise to a virtual electron-positron pair. In the quantum chromodynamic (QCD) theory of quarks and gluons, the stronger and more complicated forces give rise to a state which cannot be described as a perturbation on empty space. Instead, the physical vacuum has properties which resemble those of a physical medium. For example, the colour field is completely excluded, or at least strongly repelled, from a macroscopic volume of physical vacuum. This effect confines the quarks and gluons, which carry colour, inside the hadrons. On the scale of hadrons, quantum fluctuations make the phenomena more complex, but a simple picture postulates that the strong colour fields inside the hadron create a local volume of space more like the perturbative vacuum state, reverting to the physical vacuum state outside. This concept has been quantitatively expressed by the bag model.

This physical vacuum is also supposed to explain the origin of broken symmetries. An analogy is a perfectly symmetrical sphere of iron. Above the Curie temperature the state has spherical symmetry. At low temperature, the ground state will be magnetized, with the magnetic field pointing in an arbitrary direction determined by quantum fluctuations. The symmetry of the state has been broken, without any arbitrary direction entering in the laws of nature. By a quite similar mechanism, the parameters of the physical vacuum could determine the seemingly arbitrary breaking of symmetries in particle physics.

It seems that the physical vacuum has acquired properties reminiscent of Maxwell's ether. Maxwell introduced his ether for plausible reasons, but crucial experimental tests were found, and the theory was found wanting. In this talk I discuss experiments for testing the idea that the physical vacuum is not identical to the perturbative one (1).

Our vacuum state has no consequences for the testing of special relativity, and probably none for general relativity. Fortunately, another classical experiment on the vacuum is predicted to show striking results. The effect is due to the predicted instability of the physical vacuum state in the presence of high-energy density or matter density. Under these conditions, the lower-energy state is that based on the perturbative vacuum: empty space with real and virtual quarks and gluons traversing it, without colour confinement. This change to a qualitatively different state is in fact expected to occur as a sharp phase transition. The origin of this transition is that the physical vacuum state is supposed to arise from ordered virtual constituents which are disrupted by thermal agitations, or the colour fields of dense matter. The analogy of the iron sphere is again valid: the spontaneous symmetry breaking of the physical vacuum is a low-temperature phenomenon. The "Curie temperature" of the vacuum is of the order of the QCD scale parameter Λ.

2. AN IDEALIZED EXPERIMENT TO OBSERVE THE MELTING OF THE PHYSICAL VACUUM

Planck showed how far-reaching conclusions can be arrived at by analysing a volume of vacuum surrounded by walls in thermal equilibrium with the radiation in the interior. Let us follow him, adding equipment which will measure gluons as well as photons. In Fig. 1a we see a large box with thick walls at temperature T. The radiation emitted through a small aperture is measured. Alternatively, if we want to be sure of what happens in the middle of the box, a high-energy proton beam is sent through the aperture, and Compton scattering of photons and gluons is measured.

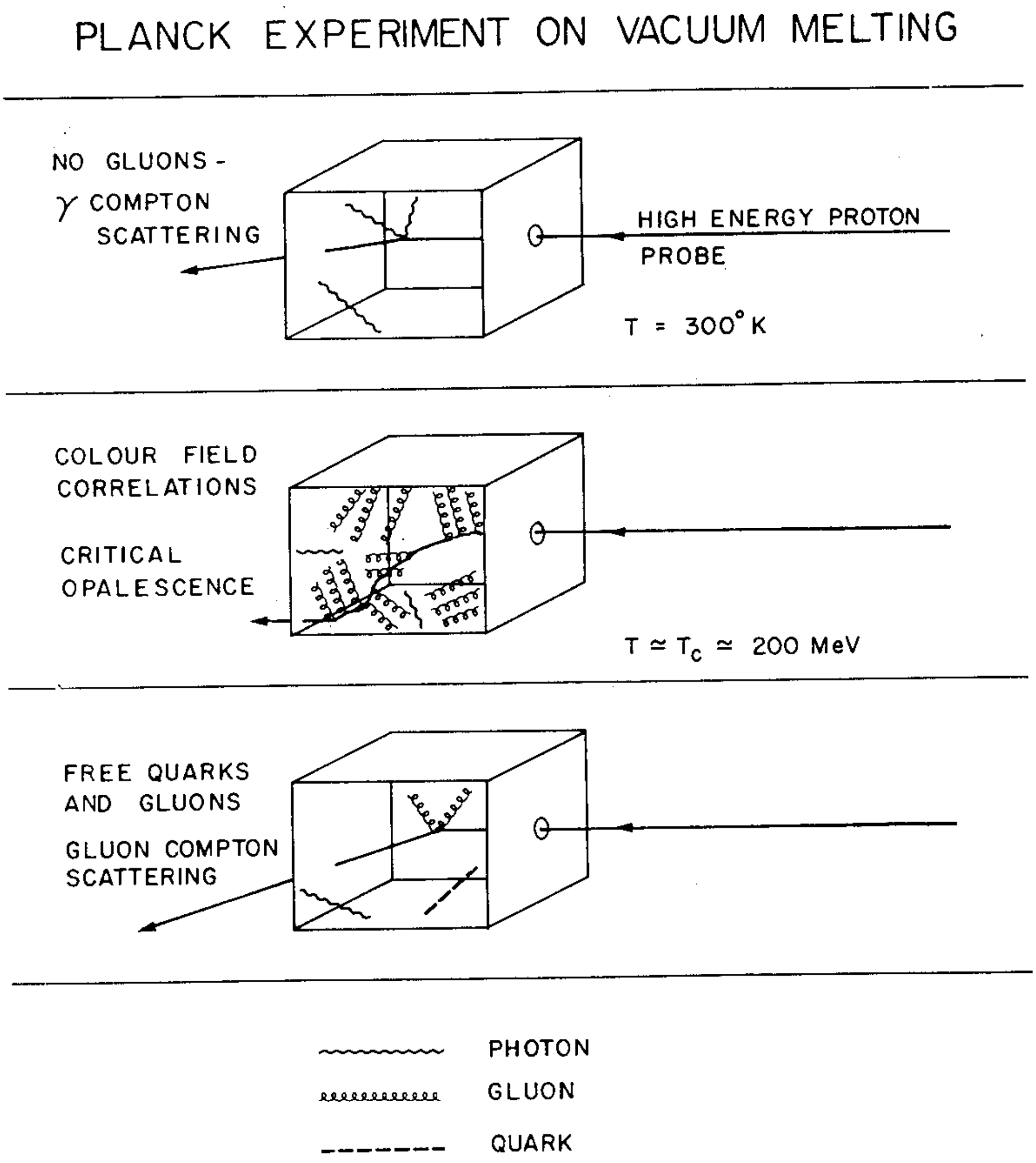

Fig. 1 Idealized experiment on "melting of the vacuum": a) Box at ambient temperature, showing thermal photons detected by Compton scattering of high-energy protons; b) at critical temperature, with large-scale fluctuations of the colour dielectric constant, and critical opalescence for protons; c) above transition, free gluons and quarks are detected in the middle of the box.

At low temperature, $T < \Lambda$, we will detect photons filling the box with the Planck distribution, but no gluons. Why not, since massless thermal gluons should be emitted by the walls? (If a mass is attributed to the gluons it is surely $<< \Lambda$.) The answer is supposed to be that the physical vacuum filling the box forces a thermal gluon back into the wall.

As the temperature of the wall is raised, there are more -- and more energetic -- thermal gluons emitted. They penetrate slightly further into the vacuum. Finally, the temperature approaches where the ordered structure of the virtual particles in the physical vacuum is so much disrupted by these assaults that the perturbative vacuum state is energetically preferred. Very near this temperature, large-scale fluctuation appears in the vacuum, with a mixture of colour-confining and unconfining regions. The phenomenon of critical opalescence will render the box opaque to the high-energy protons at that point (Fig. 1b).

Above the transition temperature, we will find freely propagating gluons and quarks filling the box (Fig. 1c). The situation at the small aperture is more complex, since it is a boundary with the physical vacuum in the world outside. Only constituent combinations which are colourless can make it to the outside world.

Suppose the walls are heated further. We note that the thermal energies of the constituents are $> \Lambda$, so that they are entering the regime of asymptotic freedom and their interactions are decreasing as they are heated. It seems there is no limit to the temperature. The "limiting temperature" observed in hadronic interactions must be a confinement effect, and indeed the Hagedorn temperature of 160 MeV is close to that estimated for the critical temperature.

The elements of this analysis which must be transferred to a real experiment are the following:

i) The size of the box. The scale is given by Λ, $\sim \frac{1}{2}$ fermi. The size must be larger than that. Evidently, the proton is not large enough.

ii) The temperature. One should be able to sweep through the region 100-400 MeV, or thereabouts. In practice, the parameter of energy density may be more useful than temperature.

iii) A sufficient degree of thermal equilibrium must be established.

iv) The probes must be able to examine the interior of the "box" -- affording measurements of sufficient subtlety to distinguish the conditions above and below the transition, and the critical phenomena.

3. REAL EXPERIMENTS

First, I will mention some possible approaches along conventional experimental lines. Consider, first, proton-proton collisions. We know that the distributions of the particles in the "beam jets" as well as in high transverse momentum jets closely resemble those in the jets from high-energy e^+e^- annihilations (2). The latter we may take to reflect the characteristics of the fragmentation of single quarks. It follows that ordinary pp collisions show no signs of the presence of many constituents, spread over a volume and in some sort of equilibrium -- the conditions we wish to produce. It is possible that some rare events in pp collisions are somewhat more suitable for our purpose, but it does not seem likely that they will go far enough towards satisfying the first three conditions above.

We can think of using protons incident on a nuclear target. Here again we can profit by a considerable body of knowledge from recent experiments (3). For example, if we consider the system in which the proton is at rest, and consider the proton fragmentation products after it has been struck by the incident nucleus, we know that they are not very different from those after the proton has been struck by another proton. Consider, instead, the nucleus to be at rest. The proton passes through, making several collisions. The fast forward products do not fragment until they have left the nucleus (see the previous remark). The slower particles are emitted at larger angles, and do fragment inside the nucleus. Their fate is a hard one, however. These fragmenting particles have energies of a few GeV or less, and they enter a volume of cold nuclear matter where they are outnumbered by "stationary" nucleons at the odds of typically ten to one. They create feeble cascades, where the creation of a few pions is partially counterbalanced by pion absorption. No wonder that the observed increase in pion multiplicity, in comparison with pp collisions, is only between two and three in the heaviest nuclei. There is no possibility of heating a large volume to an interesting temperature. Instead, the energy provided is dissipated in a large mass of cold nuclear matter.

We come rather naturally to consider nucleus-nucleus collisions at high energy. First we note that accelerators, linear or circular, act upon the charge. A fully stripped heavy ion has charge Z times that of a proton, and A times the mass, with $A \simeq 2Z$. The total energy of a nucleus produced by the accelerator is thus about Z/2 times that of a proton from the same accelerator. Even for a medium-size nucleus, say argon, this is a huge factor. Given that we needed to heat a large volume, the fact that the energy is distributed over a number of particles is not a disadvantage. Quite the contrary, since this energy can be deposited in the target with reasonable efficiency, which is of course not the case when trying to heat a nuclear volume with one very high energy proton.

To give an idea of what should happen in such a collision, I shall estimate the number of pions produced, always assuming that there is no new physics at the level of the individual nucleon-nucleon collisions. I should like to suppose that the energy is high enough so that there is a well-defined central region in rapidity, though the pion multiplicity may start to saturate at somewhat lower energies. In pp collisions, this occurs for lab. energies of about 100 GeV. In nuclear collisions, the leading quarks are further degraded by multiple collisions, and the energy required may be greater by $\simeq e^{\nu}$, where ν is the average number of collisions of the primary, ν = 2-4, depending on the A of the nucleus, or 0.5-10 TeV lab. energies per nucleon, or (for comparison with cosmic ray events) a total energy of $\gtrsim 10^{14-15}$ ev. I shall also consider only central, i.e. head-on, collisions, since we can surely select them experimentally. In the next section, I will consider the applications of non-central collisions.

Suppose the target nucleus is struck by one proton of such an energy. We know what happens: the number of pions (including π^0) is, from the CERN Intersecting Storage Rings (ISR), about 20 on the average. The effect of the nuclear target is only to increase this to about 50, and some of this increase corresponds to multiple collisions on the same nucleon, which will not contribute in A-A collisions. It should be safe to use the pp multiplicity. Consider now that the nucleus is struck at the same time but at different points; then, surely the number of pions produced is twice that produced by one proton. As the number of nucleon projectiles increases, the possibility of coherence between nearby nucleons arises. It is hard to see a motivation for such a coherence, and I believe it is not suggested by the cosmic-ray data (4). A multiplicity linear in A cannot be far wrong, and thus for A of 200, the multiplicity could exceed 4000 pions.

Naïvely, we could suppose that these pions are created in the volume of the two nuclei before the system has had time to disassemble. Note, however, that if each pion is supposed to occupy the volume attributed to it in the bag model, there is not room for that many pions. We may suppose that the matter is rather in the form of quarks and gluons, forming pions as the density falls to the appropriate value. Here, however, we make contact with the considerations on the role of the physical vacuum.

We know that the nucleus is made of nucleons, not a big bag of quarks. In fact, most of the volume inside a nucleus is occupied by the vacuum -- not by the nucleon bags. In the collisions just described, it seems very likely that the conditions are created where that physical vacuum is unstable, and at each point there is a transition to a perturbative vacuum filled with quarks and gluons. We then indeed have a big bag. The surface presumably emits pions as long as the temperature is high enough. In suggestive language, "the surface boils pions at the Hagedorn temperature". Arguments have been given that this state lasts "long enough" (5).

From another point of view, a novel aspect of the de-confining phase transition is that confinement is of necessity a long-range effect, and the transition necessarily produces long-range order. In the past, it has not been clear why there should be collective effects among many hadrons at particle physics energies. Now the confining properties of the physical vacuum guarantee such effects, within the orthodox theory. Having found circumstances where they are likely to occur, we must see if they can be observed. The problem of observables is considered in Section 5.

4. GLANCING COLLISIONS

For the study of the high-energy density states described in the previous sections, central collisions are clearly the best. We may ask if there is any interest in glancing collisions of very high energy nuclei. I believe I can suggest at least one topic for which these collisions offer a unique opportunity to study a physical configuration otherwise inaccessible: the irradiation of cold nuclear matter by an intense wave of soft pions.

To see how this comes about, consider the sequence of events in a glancing collision, as shown in Fig. 2. In Fig. 2a, a collision is shown which involves somewhat less than half the matter in the nucleus. The frame in which one of the nuclei is at rest is used. Figure 2b shows how the incident nucleus appears as a Lorentz-contracted disk which sweeps through the target nucleus. The energy deposited in this process can be estimated by an appeal to limiting fragmentation, as shown in Ref. 5. At least, this should give a lower limit to the true value. Most of this energy will be radiated as pions. Figure 2c shows the situation after the incident nucleus has passed on. The nucleons in the interacting portion of the target nucleus pick up an average velocity in the projectile direction, and the corresponding group of nucleons in the projectile nucleus is degraded in velocity. Most of the pions which reach the non-interacting piece of the nucleus are radiated from the target group of interacting

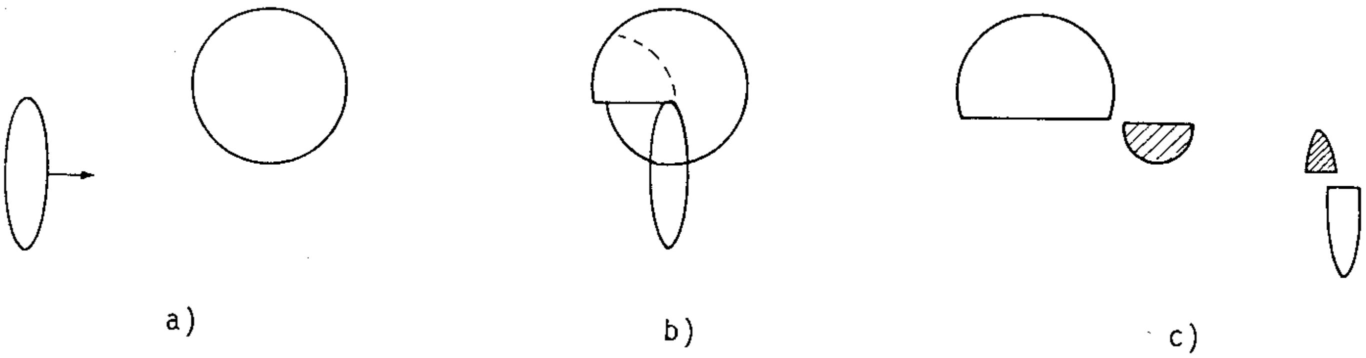

Fig. 2 A picture of the evolution of a glancing collision of a very high energy heavy nucleus, in the rest frame of the target nucleus, at three different stages.

nucleons. The kinematics are such that the pions reaching the non-interacting part of the nucleus are mostly of very low energy, in the target frame.

Though only a small fraction of all pions traverse the non-interacting portion of the target, the number can easily reach ten or more. The wavelength of these pions will be of the same order as the nuclear size. The effects of such an intense wave of strongly interacting pions may produce an interesting ordering in the nuclear matter, which may be detectable by observing the nucleons, which are unlikely to have the characteristics expected for "spectators", or by observations of the pions with velocities near that of the target.

5. THE PROBLEM OF OBSERVABLES

The literature on this subject does not provide many good discussions of the quantities to be observed. One of the weaknesses, as well as strength, of the thermodynamical method is that one can proceed happily in a discussion using the thermodynamic variables without the necessity of explaining how they are to be measured. The problem becomes acute when there are strong temporal and spatial variations. A correct procedure would be to perform a Monte Carlo simulation at the constituent and vacuum level, but that is out of reach for the moment. We cannot yet renounce thermodynamical considerations.

We can begin the discussion by noting that most of the common observables are not very useful. Most hadrons will have at last scattered near the surface of the interaction volume, largely erasing the information about their previous history. It is not sensible to go to such trouble to provide a good surface-to-volume ratio, and then selectively to observe the surface. Weakly interacting probes are called for. Most of our considerations must then deal with photons, or virtual photons observed as lepton pairs (6).

The photons in question are of course direct photons, not those from meson decays. This suggests a rare particle, of order $1/137$ compared to pions, but that can be misleading. For example, the point-like nature of the photon causes it to be much more common at high transverse momenta, where $\gamma/\pi^0 > 10\%$ beyond 5 GeV/c. More complex phenomena are probably present at low p_T, where observations, so far all depending on lepton pairs, show a relatively copious production of virtual photons (7). The virtual photons have the advantage that the mass distribution carries some information, so that the temperature of an equilibrium source could in principle be read by either the mass distribution or the transverse momentum distribution. Experimentally, they have the advantage of avoiding contamination from pion decay, though the conversion to lepton pairs costs a factor of 10^3 in rate. As A increases, the ratio of volume (producing photons) increases more quickly than surface (producing pions). This further enhances the γ/π^0 ratio, probably to values (> 10%) which can be measured directly (8).

The photons and leptons could be used in an attempt to observe the phase transition. The c.m.s. energy of the nuclei is varied, and the temperature indicated by the transverse momentum and mass distribution is determined. The rate of photon emission is then determined as a function of temperature. As the transition temperature is passed, the character of the particles producing the radiation changes, and one would expect a change in the number of the photons produced, or in the slope of the photon production versus temperature.

A variation of the baryon, or quark, density at fixed temperature will also allow a sweep across the transition. It is known from ISR data that the ratio of baryons to mesons varies strongly with rapidity. Thought the variation will be somewhat smoothed out in nuclear collisions, this will give another convenient parameter to vary in the region of the phase transition.

Since we have only rough estimates of the transition temperature (9), rather crude notions of "temperature" in pp collisions, and as yet no direct data relevant to the temperature inside nuclear collisions, we cannot say anything precise about the energies necessary to produce temperatures above the critical temperature. It seems clear that the energies investigated at Berkeley and Dubna, a few GeV per nucleon, are not sufficient. Conservative estimates in the region of limiting fragmentation, roughly corresponding to the energy range defined earlier for central region formation, seem to show energy densities of the required magnitude. In practical terms, keeping to accelerators at present existing or under construction, it seems that we must speak in terms of FNAL, SPS, ISR, or ISABELLE. Of course, experiments at 10-15 GeV/nucleon would at least allow a better estimate to be made.

Another technique of observing the new phase is based on calculations which show that heavy quarks will be much more common (10). One then has to believe that they will survive the hadronization process, which seems plausible, but not certain.

Another type of experiment which is particularly simple to carry out is the observation of collective motion of constituents. The analogy of electromagnetic plasmas would lead one to believe that such phenomena would be very prevalent in a quark-gluon plasma, but the analogy may not be very helpful, since the colour magnetic field is screened in the latter case. Such motions may be searched for very sensitively though, by looking for "jets" with more transverse momentum than generated in pp collisions. We might call these "super-jets". Since the pp jet cross-section falls rather steeply, the super-jets could stand out strikingly in a simple calorimeter experiment. The details could be quite different from a constituent scattering jet, where for example there is a strong correlation between a trigger jet and an away-side jet. The recoil of a super-jet could be carried by a large mass of plasma, giving one-jet events. The particle composition of the super-jet may be different. This would be a good place to look for the excess of heavy quarks, for instance. Most of the information for this type of experiment can be provided by hadronic/electromagnetic calorimeters.

6. TECHNICAL QUESTIONS

The energies of these experiments are in the range where high-energy physics detector techniques have become well developed, but some of the conditions are unusual. The multiplicities of thousands of particles instead of tens is a profound change, but it is accompanied by a similar change in the kind of information requested. It is a happy circumstance that calorimetric detectors, which are well suited to provide much of the information desired, actually perform better under conditions of high-energy deposit by numerous particles. Also, such detectors lend themselves to spatial subdivision into very large numbers of cells, particularly for the electromagnetic part, which is just what is needed to study photons and electrons under conditions of high particle multiplicity. I have outlined these considerations in more detail in another paper (11).

Some questions do require detailed measurement of the momentum of charged particles as well as energy flow measurement in calorimeters. Two approaches to this problem have been discussed (12). First, an inspection of these questions seems to show that if 4π coverage by a calorimetric detector is provided, the questions requiring charged-particle measurement can generally be satisfied by measuring particles over a restricted solid angle whose energy flow configuration has been identified, or selected by a trigger, using the calorimeter. The multiplicities in the detector can then be made to conform with those ordinarily handled in present detectors. Figure 3 shows how one can do this. The picture illustrates the energy flow in a hypothetical event, in rapidity versus transverse energy space. This event has been selected by a calorimeter trigger to have a "super-jet" in a special rapidity interval of small extent. There is a cylindrical drift chamber covering that rapidity interval only, but the whole azimuth. The energy flow is measured by the calorimeter over the whole solid angle.

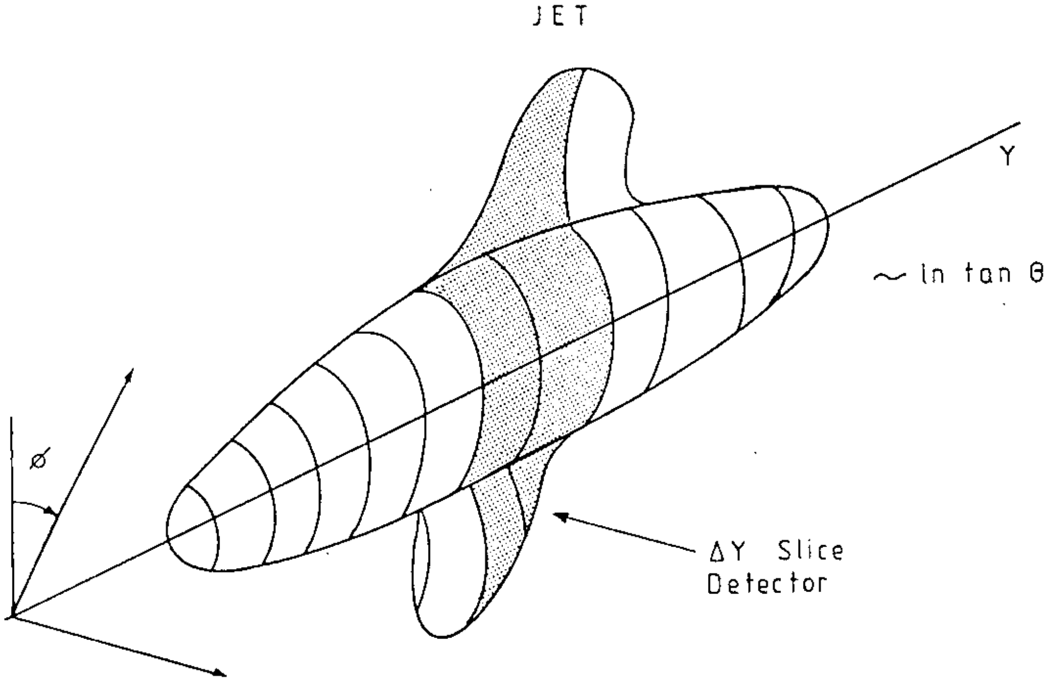

Fig. 3 A contour plot of energy flow in rapidity and transverse energy variables. The rapidity coverage of a track detector is indicated, showing how a small interval can be used to sample the jet selected by the large-solid-angle calorimeter.

A more ambitious plan would be to develop special detectors suited to the task. The requirements are less exigent than is the usual elementary particle experiment, given that the charged-particle information is needed mainly for correlation with hits in the calorimeter; that the momenta are small, at least in storage ring experiments; and that the large number of particles to be measured allows the use of methods of limited efficiency. Examples of solutions using "planar" track detectors have been described (12).

Other new technical problems arise in the acceleration of heavy particles, but those are not within the scope of this paper.

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