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EXPERIMENTS ON VERY HIGH ENERGY HEAVY IONS

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1. INTRODUCTION

In this paper I describe experimental techniques which could be used to investigate central collision of very high energy heavy ions. For my purposes, the energy range is defined by the number of pions produced, $N_\pi >> 100$, and consequently $N_\pi >> N_{nucleon}$. In this régime we may expect that new phenomena will appear.

Given the very large numbers of particles produced, it would seem that many of the familiar experimental techniques of high-energy physics cannot be directly applied. My task is to show that the most interesting experiments can in fact be done with equipment which exists, or which can be realized by a practical adaptation of existing techniques.

In order to describe experiments on such complicated states one must have some specific notions of what quantities should be measured. In the next section I set forth a conceptual framework used to select the measured quantities. Inevitably, this reflects personal prejudices, which must differ to some degree for each physicist. Other programmes of measurement might be described which would be perfectly valid, but it is perhaps sufficient to describe how one such programme could be carried out. In particular, I shall emphasize measurements in the central region of rapidity, where the phenomena seem to me particularly interesting and amenable to description in simple terms [1].

2. PHYSICS GOALS

We undertake the study of these collisions, because we expect that new phenomena will appear beyond those which might be predicted by considering the collision as a cascade of independent hadron interactions. It is possible to argue this proposition merely on the basis of the novelty of this system, since rarely do we find that we can range very far in a new direction without uncovering unanticipated new phenomena. However, in the present instance we have strongly based predictions of new phenomena provided we pass a necessary threshold in energy, though the precise form of these phenomena cannot be specified by present calculational techniques. The basis of these predictions is the theory of coloured quarks and gluons, confined by the spontaneous symmetry breaking of the physical vacuum, QCD [2]. This picture is believed by many physicists to be correct, partly on the basis of experimental evidence, partly on aesthetic grounds. The least understood part of the theory is the confining properties of the physical vacuum, which is supposed to be a complicated state, quite different from empty space. However, in equilibrium with matter above a certain temperature, the physical vacuum must necessarily undergo a phase transition to the simple, or perturbative, vacuum. It seems that very high energy heavy-ion collisions are the only practical way to study this phase transition and a wide variety of associated phenomena. It seems to me incumbent upon us to show that a proposed programme of physics with high-energy heavy ions has a reasonable chance to deliver answers on these important questions. The measurements required are sufficiently refined that they should have a good chance of revealing any completely unexpected new phenomena as well.

The present knowledge about the phase transition in the vacuum in QCD is described in several papers [3-6]. The temperature of the transition is thought to be about 200 MeV, within a factor of two. Below the transition, physical hadrons consist of quarks and gluons confined in cavities in the physical vacuum, together with the colour field coupled to them. The cavity is a region of perturbative vacuum and the quarks and gluons act there as if they were nearly free and massless. These ideas are expressed in simplified form in the bag model, the bag representing the cavity in the physical vacuum. In fact, the quantum fluctuations represented by instantons have a spatial dimension comparable to the size of the bag, so we should not expect to see sharp phase transitions in an object the size of an ordinary hadron, or a clear distinction between volume and surface phenomena. This fact is one of the principal motivations for the use of heavy ions in these studies, whereby we should be able to create regions of adequate size to obtain clean effects. As an example, Fig. 1 shows a phase-transition-like effect in a system (cold helium gas forming a cavity around a free electron) whose diameter, compared to the atomic dimension, is comparable to the ratio of nuclear diameter to instanton size. Note that the transition is already quite sharp: a 20% change in gas density produced a change in electron (plus cavity) mobility of three orders of magnitude.

On the other hand, we know enough about nuclear physics to be quite sure that nuclei are indeed made of nucleons, not free quarks in large bags. In fact we believe that most of the space inside a nucleus is occupied by physical vacuum. However, if we collide them with enough energy, we should be able to transfer enough kinetic energy to thermal energy to bring the bits of physical vacuum inside the interaction volume above the QCD transition temperature. Then we should see the discontinuities characteristic of a phase transition, and in the high-temperature phase the constituents are free to roam in a large bag. In the limit of very high temperatures, asymptotic freedom assures that the constituents in a large bag are not interacting, but at presently attainable temperatures there will be fairly large forces among the quarks and gluons, and unusual associations or long-range effects may be present.

A major concern in previous discussions of prospects for such studies is that the hadrons we observe come from the surface of the interaction volume. The phenomena which take place in the hot interior are largely obscured by the cooling and scattering near the surface during expansion. This is surely a serious problem and much of my discussion will be devoted to experimental techniques for avoiding it. Similar arguments show why proton-nucleus collisions are probably not very effective for these studies: the narrow hot region is immersed in a wet blanket of cold nuclear matter, and the reaction products must make their way through several nuclear mean free paths of the material of the target nucleus before they can be observed.

The fact that the number of pions produced in a central collision is not supposed to be very sensitive to the physics in the interior region means that we should be able to estimate it reliably by a simple model, always assuming that there is no new physics in the production process. A model which involves the least extrapolation from experimental data, and which does not contradict the cosmic-ray data, is based on the results from proton-nucleus collisions [7]. We assume that if *two* protons strike a nucleus, the number of pions produced is twice the (known) number produced by one proton. As the number of projectile nucleons becomes large, this is probably an underestimate, because pion absorption by the target nucleons is reduced as they are heated. Counting neutral pions, the multiplicity in a p-nucleus collision is about 50 for $A > 100$. Thus, for $A = A' = 200$, we may expect $\sim$ 10,000 pions to be produced.

We are curious to know in which volume this enormous number of pions is produced. This is a question ultimately answerable by experiment (polar angle dependence of two-pion interference correlation), but for the moment we must rely on modele. A simple theoretical picture which has had some success is that of Pokorski and Van Hove [8]. These authors note the large interaction cross-section of the soft-gluon constituents of the incident nucleons, compared with those of the quarks. Their picture then is that the colliding gluons scatter so as to be brought to rest in the centre of mass, while the quarks pass through retaining most of their incident momentum. In this case the pions in the central region, about a quarter of all pions, come from the gluon component, and originate in a volume which shows a Lorentz contraction by a factor $\gamma \approx (\sqrt{s}/2A) \approx 10$. Then about 2500 pions are formed in a volume of about 50 f^3, or 50 π's/f^3. This means that many π's are formed in a volume we normally ascribe to one pion. Independent of sophisticated calculations in QCD, we may doubt that the interior can really be composed of pions, and, correspondingly, we may expect to observe new phenomena, if we can find ways to probe the interior. In essence, it is claimed here that the creation of particles out of energy is an attractive route to the generation of states of high energy-density, The compression of relatively cold nuclear matter to the same energy density may be difficult.

The experimental techniques for dealing with this flood of pions will form the body of this paper, but let me hasten to point out that the pions themselves are probably not the most important particles to be measured. Whether the particles formed in the high-density interior be considered pions or gluons, they cannot reach the exterior without interacting, and those we observe are emitted at the surface. To probe the interior, we must utilize weakly interacting particles such as photons and leptons, or particles containing strange or charm quarks whose character cannot be changed by subsequent interactions. When we ask for the number of photons and leptons, we are probably in for a surprise unless we are familiar with the work of Feinberg [9]. The point is that the photons escape almost freely from the entire volume, while the pions are emitted from the surface. The ratio of photons to pions then contains a volume-to-surface ratio, proportional to $(\text{volume})^{1/3}$. If the volume is proportional to the number of pions produced, then the ratio is approximately given by

$$N_\gamma / N_{\pi^0} = k\alpha N_\pi^{1/3} \ .$$

The constant k should be of the order of one, but we can obtain an experimental value from the measurements of photon production in proton collisions. The measurements actually available are of small-mass muon pairs [10], but they can be extrapolated to zero virtual photon mass to obtain an estimate of the number of real photons [5]. The result is indeed $k \approx 1.5$. If $N_\pi = 10^4$, $N_\gamma/N_\pi \approx 1/3$. The trend with nuclear size is shown in Fig. 2. We see that studying the leptons and photons from these collisions should be an order of magnitude easier than in proton collisions. Presumably the situation is even more favourable, because the pions will surely have the standard Hagedorn distribution, with average kinetic energy about 160 MeV, while the photons, coming from the hot interior, are expected to have much higher average energies.

This raises the question of the temperature reached in the central region, as a function of the incident energy. We have only a few experimental indications. At the Berkeley Bevalac, with $\sqrt{s}/A \approx 1$ GeV, the nucleon temperature has been stated to be about 50-100 MeV, but is is not clear that this case can be extrapolated to our situation, where most energy is carried by pions. An interesting observation made on the proton collisions leading to virtual photons and muon pairs, mentioned above is that the mass spectrum below 3 GeV is consistent with thermal radiation from hadron constituents [5]. The maximum temperature reached is about $T \simeq 500$ MeV, for $\sqrt{s} \simeq 20$ GeV. Unfortunately the s dependence of this effect has not yet been established. Another useful observation is that $\bar{p}$'s and K^-'s are produced in central pp collisions in a manner suggestive of a thermal equilibrium. In this case the s dependence is shown in Fig. 3. We are encouraged to believe that we can reach the T = 200-400 MeV necessary, but probably only at top SPS or ISR energies. I am afraid that not much more can be said on this question without seeing some high-energy heavy-ion collisions.

In searching for the phase transition, we must be careful to limit the sample to strictly central collisions. This can be done by observing the forward nucleonic components. Events must be rejected if they have more than the expected number of non-interacting nucleons. The feasibility of this will be discussed in the following section.

We can now discuss possible experiments to observe the phase transition. To observe the interior of the interaction region, the experiment should measure either real photons or virtual photons through low-mass lepton pairs [11]. (The question of distinguishing those which are direct from secondaries will be discussed later.) The s dependence of the spectrum is measured. The spectral shape should allow a deduction of the maximum temperature reached for a given s. The photonic energy should be a function of the heat capacity of the hadronic matter, and should therefore show a discontinuity as the maximum temperature passes through the transition temperature, even if the transition is of second order.

Effects may be observed in hadron distributions, as in the fraction of $\bar{p}$ and $\bar{\Lambda}$ produced, or even in small changes in the p_T spectra. For example, if the "blast wave" [12] interpretation of the difference of π and p spectra at low energies is correct, we may anticipate the disappearance of this effect as the explosive dissipation of thermal energy by individual nucleons is replaced, above transition, by confinement of the constituents in one large bag in hydrostatic equilibrium with the pressure of the physical vacuum outside [13]. In this connection, it may be noted that the dynamical effects of the copious radiation of photons mentioned above have not been considered heretofore in the theoretical calculations of such a state. It has been supposed to cool by boiling off hadrons at the surface. What happens if, in the case of a large nucleus, there is a comparable cooling by radiation from the interior? A contraction of the surface at subsonic velocities or shock-wave implosion? Or a "fog" of instanton clusters in the supercooled interior?

The observation of the phase transition would be a great step forward for QCD, comparable to the Ω^- in the history of SU(3) or the discovery of the Z^0 for the electroweak theory. However, the most important aspect of the observation is that it would give us the criteria of identifying states known to be above transition. These are then known to be states of quarks and gluons free from the effects of confinement, within a large volume. They may display effects quite different from those in the known hadrons. We should consider a few experiments to illustrate the study of this new state of matter.

The presence of strong temperature gradients, and the effects of the two streams of non-equilibrated quarks, may lead to strong large-scale instabilities, resulting in chunks of matter being emitted in a random direction from a central collision. The result will look something like a jet in pp collisions, but with a different origin. The total p_T in these jets could be much larger than that to be expected from the collision of individual nucleons. We shall see below that a search for such events can be very sensitive. The chunks themselves might have special composition, e.g. pure gluons, all strange quarks, etc.

Two-pion or two-photon interferometry would appear to be an important tool for the study of those collisions [14]. This has never been very fruitful in pp collisions, because so few events have two pions at the required close distance in phase space. However, this fraction goes with the square of the multiplicity, and for the events we are considering, the situation is completely reversed. One may almost speak of a classical pion wave. By a Fourier transformation we may obtain a picture of the events. If photons are indeed present in comparable numbers, the same is true of them. The photons give a picture of the interior, while the pions image the surface.

More detailed experiments on these states can be done by taking advantage of the rare hard processes among individual hadron constituents. For example, we know that the so-called QCD Compton process shown in Fig. 4 has an appreciable cross-section for $p_T \approx 6$ GeV [15]. The photon passes freely out of the central region and can be detected. The quark must traverse the volume filled with hadronic matter, giving us a sharp probe of the condition of that matter. The elementary process is known to have a tight angular correlation, in the azimuthal plane, allowing us to identify scattering of the quark. The selection of the cases where the quark fragments into a leading pion simplifies the measurements, at the cost of a factor ~ 100 in rate.

Finally, we may ask what role we expect to be played by measurements on individual particles, as distinct from global experiments, or those analysed as probes of global properties. Here, the particular values of these collisions is presumably as a pressure cooker of constituents, more suitable for concocting strange mixtures of quarks than are pp collisions. A specific and plausible prediction lies at hand. In the bag model, some unusual six-quark states are expected to be *stable* under the strong interactions [16]. For example [5], the system

$$(u^2d^2cs) \rightarrow \Lambda\Lambda \text{ or } \Xi^- p \ .$$

These states may be very hard to make in pp collisions, but might be produced more copiously in very high energy heavy-ion collisions.

3. CALORIMETERS

Many of the measurements described above can be performed by the use of calorimeters only, with designs which actually exist, and with much higher accuracy than is usual in calorimeter experiments. For that reason it is worth while to describe here the recent advances in the understanding of the potentials and limitations of calorimeter performance [17].

By calorimeter we mean a detector which absorbs all the energy of a particle by a cascade of interactions, detects the sum of energy in all the resulting particles, and gives an output ideally proportional to the total energy released: the kinetic energy for a proton, kinetic energy plus two proton masses for an antiproton, total energy for a pion, etc. The first requirement for such a device is that it be thick enough to contain a large fraction of the energy in the cascade, typically about four nuclear absorption lengths for hadrons of a few GeV and increasing logarithmically with energy. For that thickness, the response to a single particle will be a nearly Gaussian peak, with a small tail at low apparent energies from particles which have only interacted near the end of the calorimeter, if at all. Detecting a jet of particles with the same total energy, there is an average over these fluctuations, and the tail of low response is suppressed. This will be the case with the high-multiplicity heavy-ion collisions, and would even allow the design of calorimeters substantially thinner than normal if that were advantageous.

Many different techniques have been used to detect the energy deposited in the calorimeter, such as ion chambers in gas or liquid, gas proportional counters, scintillation detectors in liquids or solids, and Čerenkov detectors [17]. Usually the calorimeter is divided into many layers of inert absorbing material and active medium, the so-called sampling technique. From event to event, there will be a different fraction of energy deposited in the active medium, and this sampling fluctuation sets one limit on the energy resolution. If there are N_s sampling layers, then the sampling fluctuation for energy E is found to vary as $1/(N_s E)^{\frac{1}{2}}$, with a coefficient which is about twice as large for incident hadrons as for incident electromagnetic particles (photons and electrons), owing to the more catastrophic character of hadron collisions [18]. In most calorimeters, the electromagnetic particle resolution is limited by sampling fluctuations up to the energy where technical limits in the read-out are more important. Typical calorimeters with sampling every radiation length give energy resolution [19]

$$\sigma_\gamma = 0.12 \left[E(\mathrm{GeV})\right]^{\frac{1}{2}} .$$

For hadrons, there is another effect which is often limiting. This is due to the different response of the calorimeter to electromagnetic and hadronic particles. The response of a sampling to an electron, for example, is found typically to be about 20% lower than might be expected from a calibration with non-interacting muons, but the response of an iron calorimeter to protons at a few GeV, where pion production is not very large, is found to be still lower than to an electron of the same kinetic energy by a factor of about 2/3. Detailed simulation calculations show that this is due to energy spent in disrupting nuclei, poor response of the active medium to slow heavy particles, missing neutrinos from pion decay, loss of slow neutrons, and other causes [20]. When pion production is important, there is a large fluctuation from event to event in the fraction of energy which goes into π^0's in the first one or two generations of the cascades. This, combined with the difference in response, leads to a serious broadening of the response for hadrons. There are some cases where the response is equal to that for electrons, corresponding to events where the cascade is largely electromagnetic, but the average response is much lower. For this reason it is not useful to make sampling with iron plates thinner than about 10 mm, for example [18]. This effect gives a resolution in iron, copper, or lead of about [21].

$$\sigma_E = 0.55 \left[E(\mathrm{GeV})\right]^{\frac{1}{2}} .$$

Two methods have been employed to reduce this effect. The first takes into account that there is a correlation between the fraction of electromagnetic energy and the longitudinal development of the cascade in iron. These cascades, which are rich in electromagnetic energy and consequently give a relatively large response, have a rapid longitudinal development. Thus, if the calorimeter is sufficiently longitudinally segmented to observe the development, this correlation can be used to improve the energy resolution. Abramowicz et al. [22] find $\sigma_E = 0.93[E]^{\frac{1}{2}}$ at E = 140 GeV, but $\sigma_E = 0.58[E]^{\frac{1}{2}}$ after taking advantage of this correlation. The improvement is less at lower energies. This technique is applicable for single particles at relatively high energies. If there are several nearby particles, their different initial interaction points obscure their individual longitudinal development, and this method cannot be used.

The other technique uses a fissionable material and takes advantage of the fact that electromagnetic cascades give rise to little fission, while those hadronic processes which give smaller response in the calorimeter give rise to a substantial amount of fission. The fission fragments do not escape from the absorber layers, but the prompt nuclear photons and fast neutrons can carry out enough detectable energy to increase the response to hadrons relative to electromagnetic particles. Using ^{238}U, the response can be made approximately independent of the type of incident particle. This means that one can measure jets without a bias toward those containing an anomalously large fraction of electromagnetic particles. Also the resolution is substantially improved, as illustrated in Fig. 5. The component due to the nuclear effects becomes [18]

$$\sigma_E = 0.25 \left[E(\mathrm{GeV})\right]^{-\frac{1}{2}} ,$$

though to approach this value the absorber plates have to be of the order of 1 mm thick and correspondingly numerous. A more practical design with 3 mm thick plates can have [23]

$$\sigma_E = 0.32 \left[E(\text{GeV})\right]^{-\frac{1}{2}} .$$

The spatial resolution is limited by the transverse spread of the cascade. Sampling calorimeters contain 90% of the energy of an electromagnetic shower in a cylinder of radius 10-30 mm depending on the density of the construction. In the case of hadron cascades, the transverse spread is controlled largely by the neutron transport, especially in iron, where the inelastic scattering cross-section is small. In a high-density design, the cascade is contained in a 20 cm radius in an iron calorimeter, or about 12 cm in a uranium calorimeter.

The question of spatial subdivision of the calorimeter is closely connected with the methods of read-out, and these are too diverse to discuss in this brief presentation. In fact, means have been found to provide adequate spatial subdivision with all of the detection methods mentioned earlier. Even scintillation light can be piped out through thin sheets, using the wave-length-shifting technique [24]. The limit is usually the cost of electronics for large numbers of channels.

The calorimeter is always divided into at least two longitudinal sections in order to distinguish between electromagnetic and hadronic particles. The transverse subdivision appropriate to the electromagnetic (front) section of the calorimeter is an order of magnitude finer than that for the hadronic part, given by the transverse size of the cascades. The hadronic part has relatively few elements and is often read out in independent elements or "towers". This is not so common for the electromagnetic section, where instead the read-out is often in the form of interleaved strips at different angles, giving a stereoscopic reconstruction. The drawback is the possibility of reconstruction ambiguities.

The most important question in detector design for the physics of high multiplicities we have described seems to be the required granularity of the electromagnetic calorimeter. For the heaviest nuclei, we must deal with 10^4 particles distributed (uniformly?) over 6-8 units of rapidity. Take 1000 particles per unit rapidity as an example. If we wish to observe the radiation of direct photons from the interior region, we must distinguish them from pion-decay photons. The average energy of the decay photons is half the total energy of the pion, which has an average kinetic energy of 160 MeV. The decay photon energy is then $\frac{1}{2}$ (160 + 140) = 150 MeV. The photons are radiated from a system starting at a high temperature, say 600 MeV, cooling until it reaches the hadron boiling temperature of 160 MeV. Thus the most interesting region is that from 200-800 MeV, in the c.m.s. (The fixed-target case will be considered later.) Above 200 MeV we expect that the background from pion decays will be small enough to be subtracted, leaving a direct photon signal with a good signal-to-noise ratio. In this energy range, most of the energy is deposited in the first six to eight radiation lengths of the calorimeter, and it is this region which should be suitably subdivided, while the remaining energy will be recorded in the more coarsely subdivided calorimeter behind. To make sure that there is an adequate efficiency to have only one particle in one of the fine cells, there should be an order of magnitude more cells than particles or $\sim$ 10,000/unit of rapidity. (This is over the whole azimuth. The *number* required depends on the solid angle required, to be discussed later.) If the cell size should be at least $(2\ \mathrm{cm})^2$, to contain the transverse spread of the energy, $4\ \mathrm{m}^2$ $(10^4 \times 4\ \mathrm{cm}^2)$ are needed and the detector must be at least 1 m from the source to have the required granularity. A detector of relatively low density would need to be at about 2 m. These considerations show that the task can be carried out with detectors of reasonable dimensions. It also shows that the use of strips for read-out is not feasible when so many distinct elements are required. Examples of tower read-out of electromagnetic calorimeter exist in the lead-glass arrays [25] of JADE and GAMS, and with sodium iodide [26].

If the experiment is done on a fixed target, the maximum of the energy scale is increased to several tens of GeV, which is an advantage from the point of view of energy resolution, but the detector must be somewhat deeper, and there are inconveniences associated with the c.m.s. to lab. transformation, of which the most serious is the dynamic range problem. The area required is the same, but it is placed at a suitable distance in the forward cone.

Another interesting case to examine is the problem of separation of high p_T π^0's from direct photons. The use of the high p_T direct photons as a tag for quarks in order to probe the interior of the interaction volume was mentioned in Section 2. In the case of the low p_T π^0's, it is impossible to reject individual decay photons from individual events, because the decay cone includes many photons of similar energy. At high p_T, the decay cone is small enough so that the correlation of the two decay photons allows a considerable fraction of the π^0's to be rejected. For example, at a distance of 1 m, 6 GeV π^0's will have a median separation between the two photons of about 50 mm. In a detector with 20 mm cells, the π^0 will usually be recognized as two showers or one wide shower, inconsistent with a single photon. Very asymmetric decays cannot be identified, leading to a limit on the pion rejection factor of about five to ten. It is interesting to note that the granularity of the subdivision required for this task is just about the same as that needed to handle the high multiplicity of low-energy particles.

An important function of the calorimeter is to identify the central collisions. These are recognized by the distribution of the forward nucleons. In a central collision on a medium to heavy nucleus, essentially all the incident nucleons should interact except those in the outermost annulus, where there is less than one mean free path of nuclear matter. The forward calorimeter should be able to distinguish, statistically, between non-interacting nucleons, with the full incident energy, and those which have interacted, which retain about 0.6 of the incident energy. This 40% difference is easily resolved by the calorimeter. Angular resolution is also necessary, at least to distinguish the forward nucleons from the beam. This would require several metres of lever arm for 15 GeV nucleons, and proportionately longer in fixed-target experiments.

The calorimeter should cover essentially the whole solid angle, whether the experiments are conducted with colliding beams or with a fixed target. Many important experiments can be carried out with the calorimeter alone, but it plays an equally important role in providing a selective trigger and an over-all picture of selected events where the main analysis depends on the fine-subdivided calorimeter or tracking chambers. Even the coarsely divided calorimeter, where the cells are $\sim (20\ \text{cm})^2$ to match the size of the hadron cascade, has several thousand outputs if it covers the whole solid angle. Techniques have been developed for dealing with this number of signals at event rates up to 5×10^6 per second, and these will now be briefly outlined.

With only 200 ns available per event, it is difficult to use digital techniques, but a good deal of analogue computation may be done. The method chosen in the Axial Field Spectrometer at the CERN ISR operates on signals summed along rows at constant azimuthal angle, giving a one-dimensional picture of the event [27].

In fact, in pp collisions, most angular features are much more prominent in the projection normal to the beams. The sums are made directly at the detector, separately for the electromagnetic and hadronic sections of the calorimeter. These sums, about 100 in this case, are brought to the trigger electronics on short, fast cables, while the 3000 signals from individual cells are sent along longer, slower cables. In this way, about 200 ns are generated in which to make a decision on the registration of the whole event. In this time, the azimuthal signals are examined for clusters of the appropriate size for electromagnetic single particles, hadronic single particles, and jet cascades. These are classified according to size, and code words are generated to identify events containing different numbers of various types of clusters. Indications are also made of the level of total transverse energy, and of transverse momentum inbalance. Relevant information from other fast detectors is also provided. Independent logic units are plugged into a very fast signal bus containing this information. In this way, different experiments may be carried out without disturbing the triggers of the others. Complete facilities are provided for introducing calibrating signals of known size on each channel for trigger check-out. When a trigger is satisfied, the event is recorded for further analysis by digital techniques, which are, in the first instance, carried out by a fast microprogrammed processor. At this stage, the full two-dimensional information is used.

A system of this sort can be used to generate extremely selective triggers, by factors much greater than 10^6. Rare events can be chosen, and their most interesting features can be required to fall in the solid-angle regions covered by special detectors.

4. TRACKING

I have been at some pains to show that an important physics programme could be carried out without any tracking of charged particles. However, we recognize that there are other experiments which require the tracking of individual charged particles. It will be important to measure inclusive spectra of identified particle types, but this can be done with small-aperture spectrometers without any novel difficulties. More challenging is the task of searching for V^0's and novel decay modes. For example, the quasi-stable multiquark states mentioned in Section 2 may live long enough to traverse a focusing spectrometer. If so, their detection is easy. More likely, their flight paths will be measured in centimetres, and the search must be conducted by identification of the decay products, two $\bar{\Lambda}$'s for example.

For this purpose, a detector capable of full pattern recognition over a substantial solid angle is required, and one must face the problem of dealing with the high density of particles anticipated. Some comfort can be drawn from the fact that the local density of particles in the c.m.s. is not much higher than that seen in the middle of a jet from high-energy e^+e^- collisions, at PETRA for example, and indeed even lower than in the forward jets at the SPS. This suggests a simple step towards a practical solution to this problem, that is, to cover a region of solid angle which is just as large as can be handled by conventional techniques. If this is not large enough to cover the correlations of interest, several such detectors can be placed adjacent to each other, with independent read-outs and minimal dead regions.

The electronic detectors now working with the greatest multitrack handling ability are the JADE [25] central detector and the similar AFS drift chamber [28]. A picture of a high-multiplicity event in the latter device from αα collisions is shown in Fig. 6. This type of chamber can handle 50-100 tracks over the full azimuth. Soon to be operating are the TPC at SLAC and the UA1 detector at the CERN $p\bar{p}$ collider, with their essentially three-dimensional read-out, which should have a larger multi-track capability. We may also consider that computational costs set a limit on the number of tracks to be recorded, but if that were the only consideration one might prefer to compute fewer events and have them more complete. It is clear that, to carry out a given measurement, it is necessary to choose the shape as well as the size of the solid-angle coverage very carefully. For investigations of decay or fragmentation processes at large polar angle, an approximately square configuration is presumably the best. An angular coverage of 60° would allow the measurement of any correlations that could properly be called local. According to our calculations for the highest multiplicities, 1000 per rapidity unit, this detector would see about 250 particles. This density could be handled by TPC chambers, perhaps subdivided in the UA1 manner. A streamer chamber optically divided into two halves could probably handle this solid angle, or one a bit smaller in the direction of view. As usual, the calorimeter information can be used for triggering, and to examine the remainder of the event. The orientation of the magnetic field is clearly not very important for this type of spectrometer.

For investigating the over-all dynamics of the event, other configurations may be more appropriate. For study of large-angle phenomena, the usual axial-field magnetic configuration is probably most convenient. The chamber configuration of the type which generated Fig. 6 could be used, with the dimension along the wires reduced to the necessary degree to give a rapidity coverage corresponding to a tolerable multiplicity. In the case of the highest-multiplicity reactions, this would be about 0.1 unit of rapidity, to give $\sim$ 100 particles. This would provide an azimuthal cross-section view of the event, with the calorimeter trigger selecting events where the feature of interest is centred on this rapidity slice. The measurement of dE/dx in such a chamber allows the identification of essentially all protons and nuclear fragments, and a good fraction of the K's, at low p_T.

The intermediate- and forward-angle regions are important for investigating matter containing a larger fraction of the original quarks. In this case, a more useful cross-section through the event is one in a plane containing the incident beams, and covering a limited range of azimuths. This configuration is well suited to a dipole spectrometer, good examples of very open structures being the split field magnet (SFM) at the ISR or the Omega spectrometer at the SPS. The small azimuthal range dictated by the limit on multiplicity can be accommodated by a small magnet gap. Associating this fact with the relatively shallow calorimeter required in these experiments suggests that existing dipole spectrometers could be adapted to provide nearly full calorimeter coverage in addition to charged-particle tracking.

This discussion has been slanted towards the use of existing spectrometers. If it were ever deemed necessary to build a new major facility for these experiments, practical means might be found to provide charged-particle detection over the whole solid angle, despite the large number of particles. The key to this possibility is to recognize that conventional tracking detectors are required to have a very high reliability in their measurements, particularly on high momentum tracks, so that one can go far out on the tails of steeply falling functions of p_T or mass with confidence. If the detector is required to do a very different job, that is to measure many particles of a few hundred MeV/c in the c.m.s. with mistakes in momentum allowed in a few per cent of the measurements, drastically different tracking schemes become possible. For example, consider a detector where the source of particles is small, in two dimensions at least, and the particle direction is measured after traversing a magnetic field. If the angle measurement is made on a very short lever arm, the detector is more nearly a surface than a volume. The measurements and the analysis programmes may then work on a local basis, and the pattern recognition could even be integrated with the read-out. It would not be appropriate to pursue the details further here, particularly since we cannot now see clearly the necessity for such detailed information.

5. LEPTON MEASUREMENTS

In situations where direct photon production remains small compared with that for neutral pions, the most reliable method of determining it is to extrapolate from small-mass lepton pairs. For such an extrapolation to be meaningful, the lepton-pair mass must be well below the ρ^0 mass. On the other hand, for electron-pair masses less than half the pion mass, there is a large background due to internal conversion of pion-decay photons. The mass region of interest is then approximately 100-600 MeV. If one chooses the work with muons, the available range is 210-600 MeV. In return for the cleanliness of the method, one has to pay in rate by a factor $\gtrsim 10^3$, compared to the direct photon measurement.

Clearly, a good identification of the leptons is essential. Usually the muons are identified by their passage through an adequate number of interaction lengths of matter, while electrons are identified by their electromagnetic cascade development in conjunction with a mass measurement by means of Čerenkov or transition radiation, or by relativistic rise in ionization. This method of muon identification is not very effective for low-energy muons, where the absorber thickness is limited by range and multiple scattering. It is successful in fixed-target experiments, where the centre-of-mass motion imparts an adequate energy to the muons, or in measurements of high-mass muon pairs at rest. The methods of electron identification are somewhat more complex, but are applicable over a wide momentum range. In these circumstances, it is natural that electron detection tends to figure prominently in colliding-beam experiments, while most fixed-target experiments have concentrated on muons. We would expect that these trends would largely continue in the study of heavy-ion collisions, subject to the following consideration.

One of the advantages of muons in fixed-target experiments is the possibility of the so-called "beam dump" experiment. A high-intensity beam strikes a dense block of material adequately thick to absorb hadrons, and the emerging muons are measured. Such an experiment can be very sensitive, and it has been verified that the results are quite similar to those on a hydrogen target. In the case of a heavy-ion beam, such an experiment would be dominated by peripheral collisions. To observe the less common central collisions and the interesting phenomena we expect to find there, we must have a rather thin target, and trigger on the characteristics of a central collision as revealed in the forward nucleons, event by event. A reasonably long lever arm between the target and the detectors of these forward nucleons is necessary in order to measure the angles adequately. For example, to translate 100 MeV/c of transverse momentum of a 100 GeV/c nucleon into 50 mm of transverse displacement, a reasonable requirement given the number of particles in the forward cone, a 50 m drift distance is required. This poses a problem for muon identification, since a typical muon momentum of interest is around 5 GeV/c, and 10% of 5 GeV/c charged pions decay to muons in such a distance. Since the interesting muons tend to lie at somewhat larger angles, it may be possible to arrange shorter flight paths for them, but alternatively electron identification, which does not suffer from this problem, may tend to become more attractive for fixed-target as well as colliding-beam experiments. In any case, it should be emphasized that these experiments can be carried out with adequate precision to see effects even much smaller than those expected.

6. DETECTOR FACILITIES

The previous sections have described some important experiments and the detector techniques which would enable them to be carried out. Here we make a few comments on the systems aspects, in particular the probable differences of large-detector facilities for very high energy heavy ions compared with those in other areas of high-energy physics.

There has developed a difference in style between detector facilities designed for e^+e^- collisions and those for hadron collisions. The former usually aim to be as homogeneous as possible over the full solid angle, except perhaps at extreme forward angles, while the latter often have specialized detectors covering portions of the solid angle. There are reasons for this difference in the nature of the physics to be studied. The rate of e^+e^- events is relatively small, and because of the point-like nature of the interaction, every event is of interest. Naturally, under these circumstances, it is desired to have as complete and uniform a view of each event as possible. In the case of hadron reactions, the total rates are much higher, but one is usually looking for a small subset of the events with particular features. Considerations of cost or experimental practicality often dictate that a specialized detector arm be employed over a portion of the solid angle, sometimes in correlation with another arm of different properties covering another sector of the solid angle.

It seems likely that the collisions of very high energy heavy ions constitute a case with still different characteristics from the facility point of view. The central collisions must be selected, to be sure, but they constitute a substantial fraction of all events, by hadronic standards. Each of them should be interesting in the first instance, by an argument which is just the opposite extreme of that for e^+e^- collisions: the large number of constituents should ensure reproducible phenomena. We can foresee a further stage, where rarer events are selected in searches for plasma instabilities or hard elementary scattering probes. In all cases, it seems as if the main parameters of the event will not depend on any particular particle, but on flow of energy, and number and type of particles. It follows, as we have emphasized, that complete calorimeter coverage is essential for most experiments. At the same time, the very high multiplicity allows and perhaps requires detectors which sample particles in relatively small parts of the solid angle. These smaller detectors might even be the responsibility of different groups. In this way, the peculiar technical features of these experiments might lead to a novel form of organization. This should be taken into account in the design of the facilities.

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Figure captions

Fig. 1 : The mobility of electrons in gaseous helium as a function of inverse temperature, from H.R. Harrison and B.E. Springett, Phys. Lett. 35A, 73 (1970). The formation of a cavity in the gas surrounding the electron is shown. The interest in this system is that the ratio of the size of the atoms to the cavity is similar to the ratio of the size of the nucleons to the heavy nuclei. It gives us an idea of how sharp phase-transition effects can be expected to be.

Fig. 2 : The predicted ratio of direct single photons to neutral pions, at low p_T.

Fig. 3 : The production of K^- and $\bar{p}$ in pp collisions as a function of centre-of-mass energy.

Fig. 4 : The diagram for "QCD Compton scattering", A quark absorbs an incident gluon and emits a photon. The photon could be used to tag the scattered quark, whose interactions inside the nuclear volume could be deduced.

Fig. 5 : The comparison between energy resolution in an iron - liquid-argon calorimeter and that in a uranium - liquid-argon calorimeter.

Fig. 6 : The AFS drift chamber, with an α-α collision at $\sqrt{s}$ = 126 GeV, showing a collision producing 45 tracks in the central half of the rapidity space. A similar picture would result from a similar chamber with a much smaller axial dimension, exposed to very high ($\sim 10^3$) multiplicity events, allowing inspection of the events by a "sampling" technique.

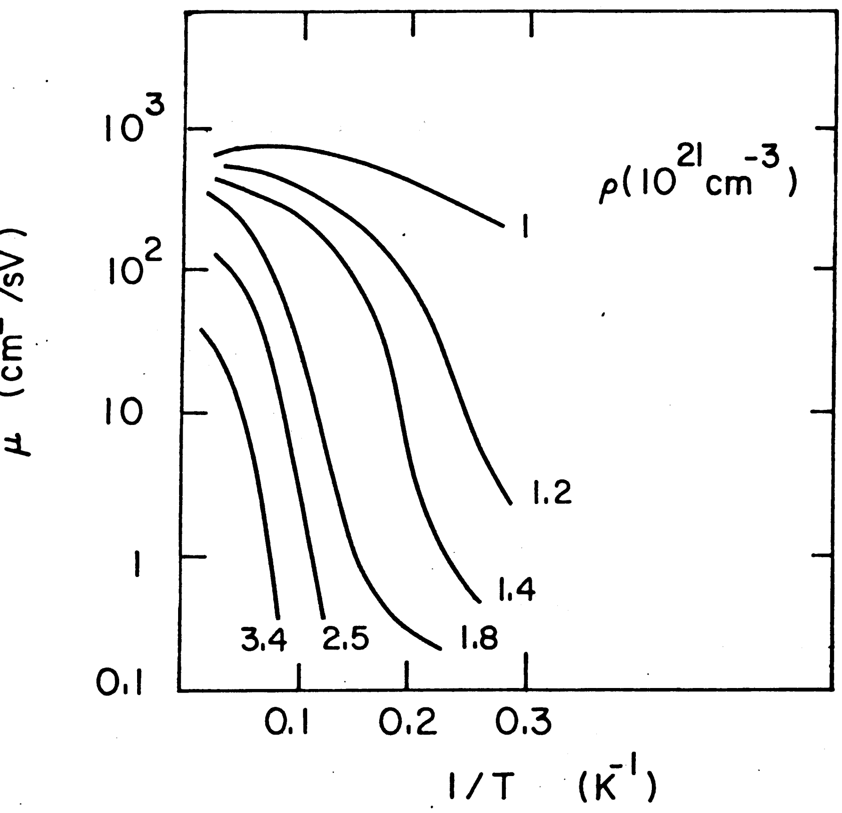


Fig. 1

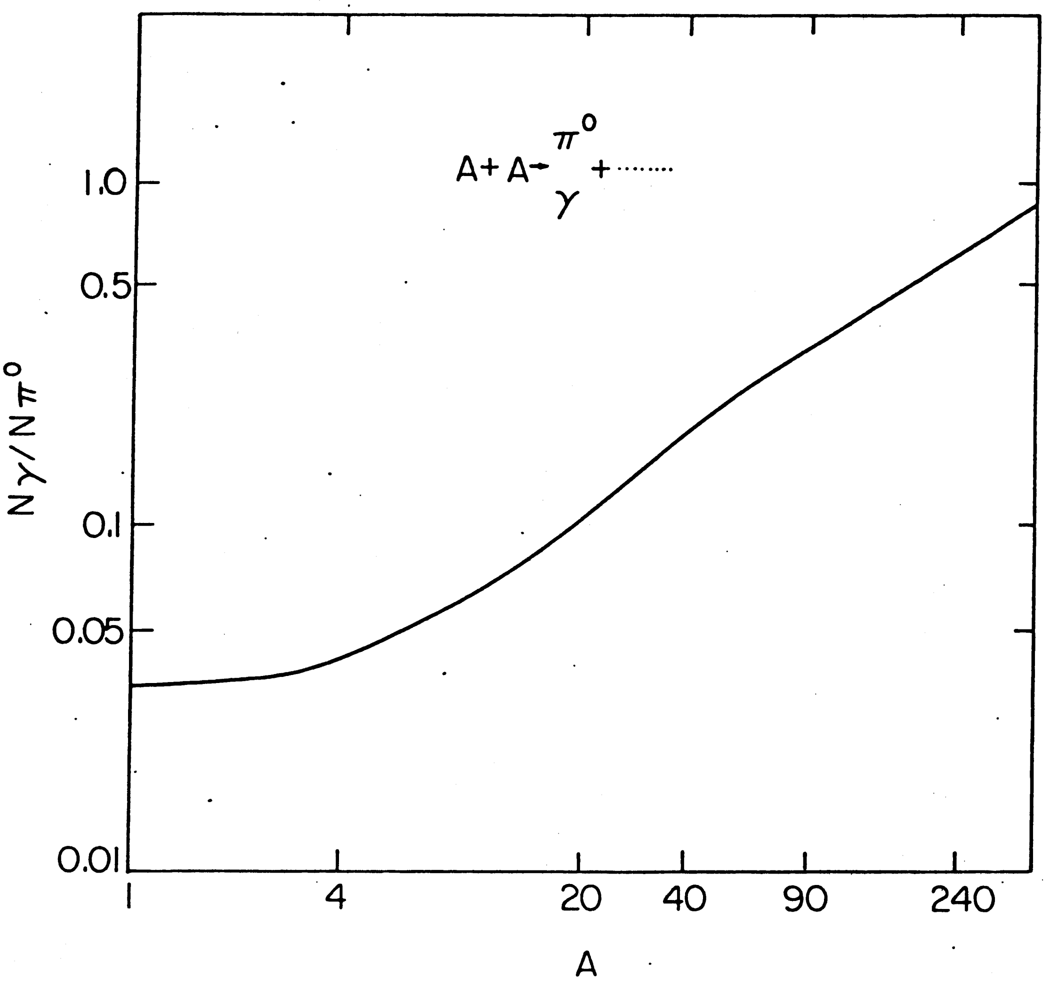
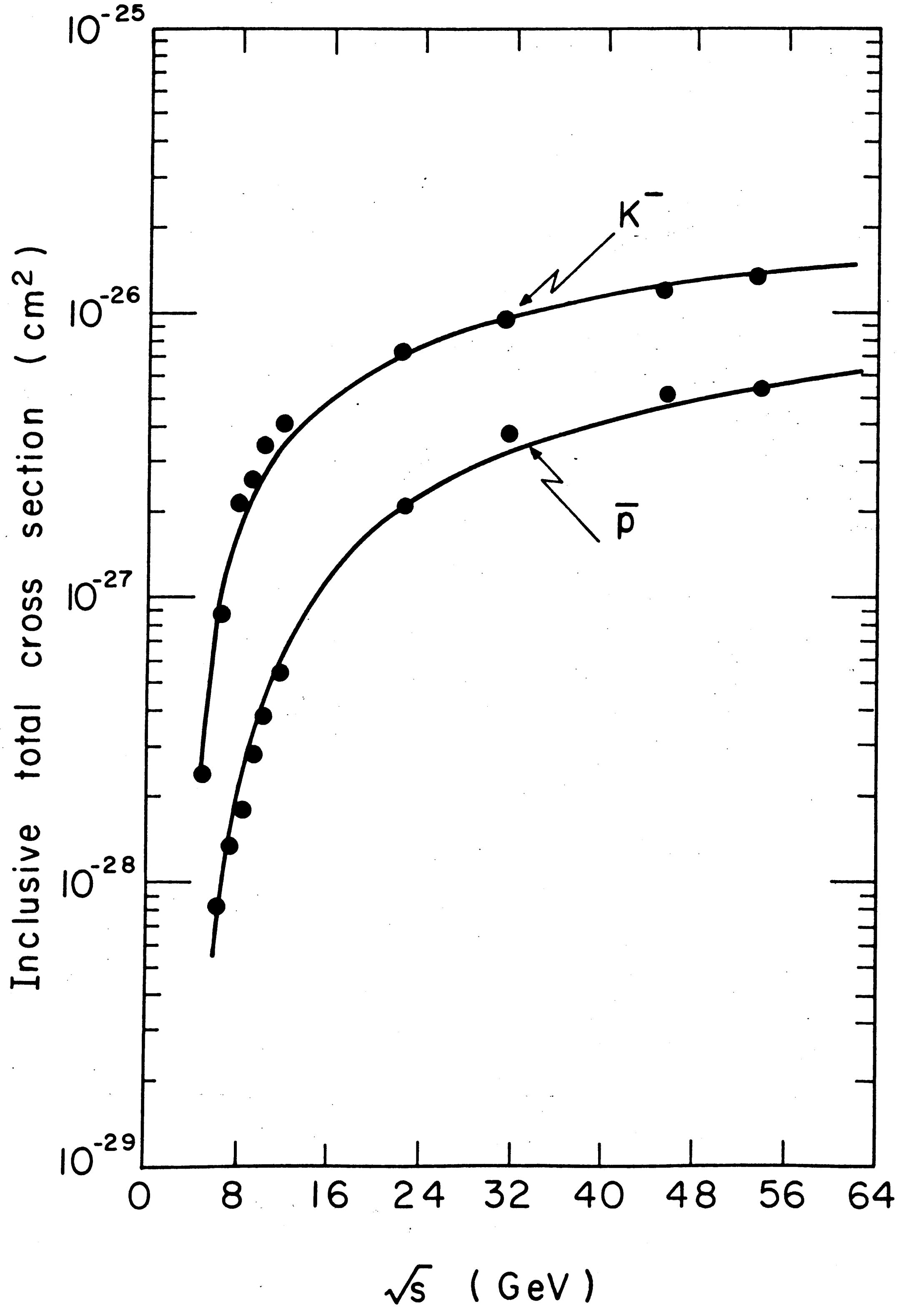


Fig. 2



Inclusive total cross section (cm²)
10⁻²⁵
10⁻²⁶
10⁻²⁷
10⁻²⁸
10⁻²⁹
K⁻
p̄
0
8
16
24
32
40
48
56
64
√s (GeV)

Fig. 3

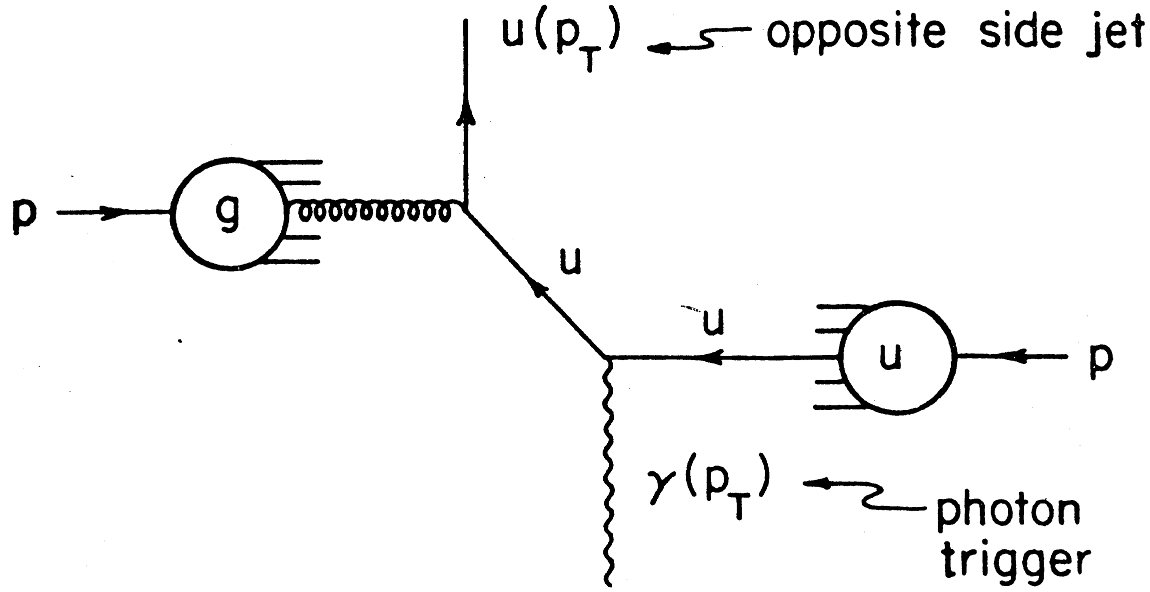


Fig. 4

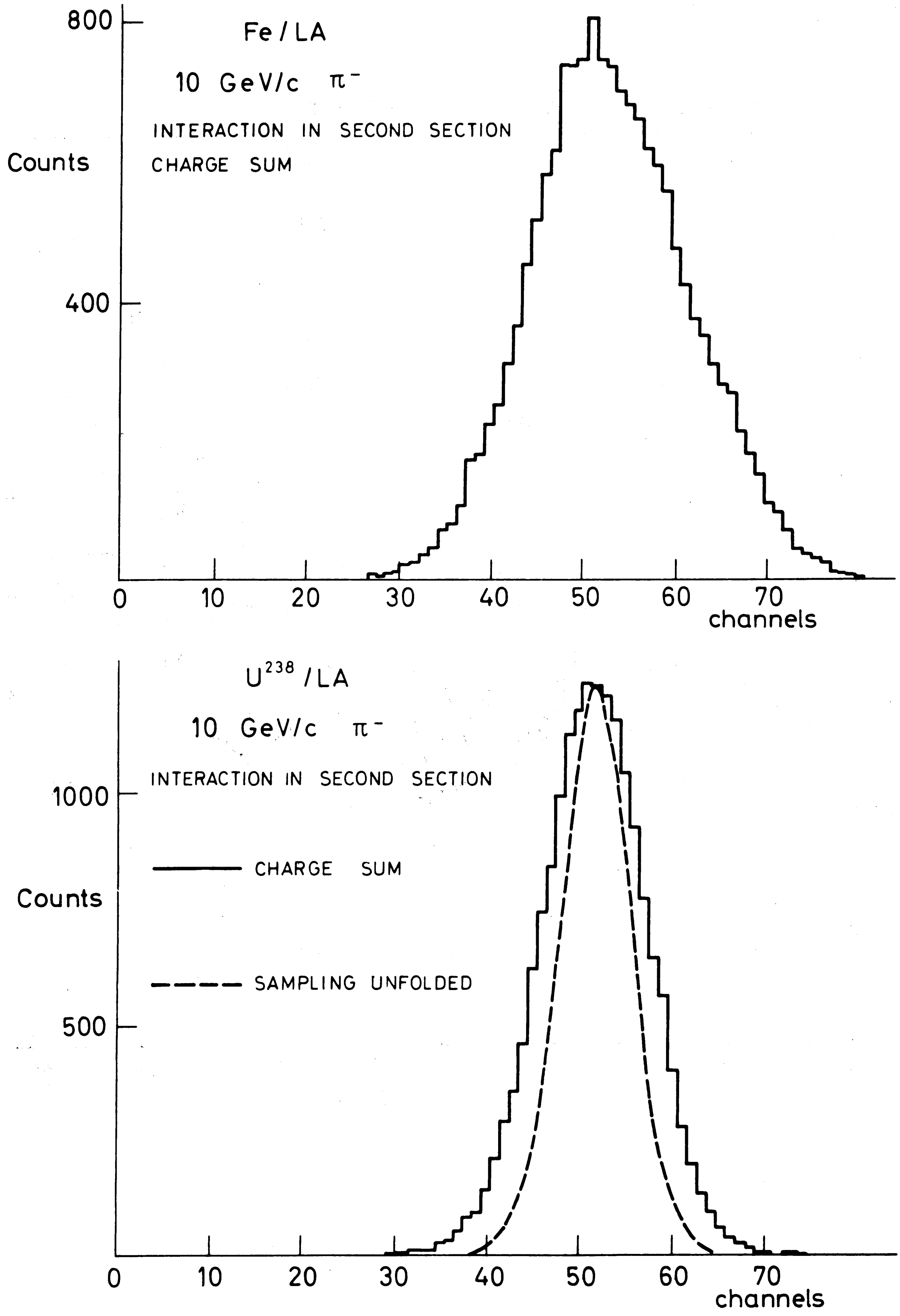
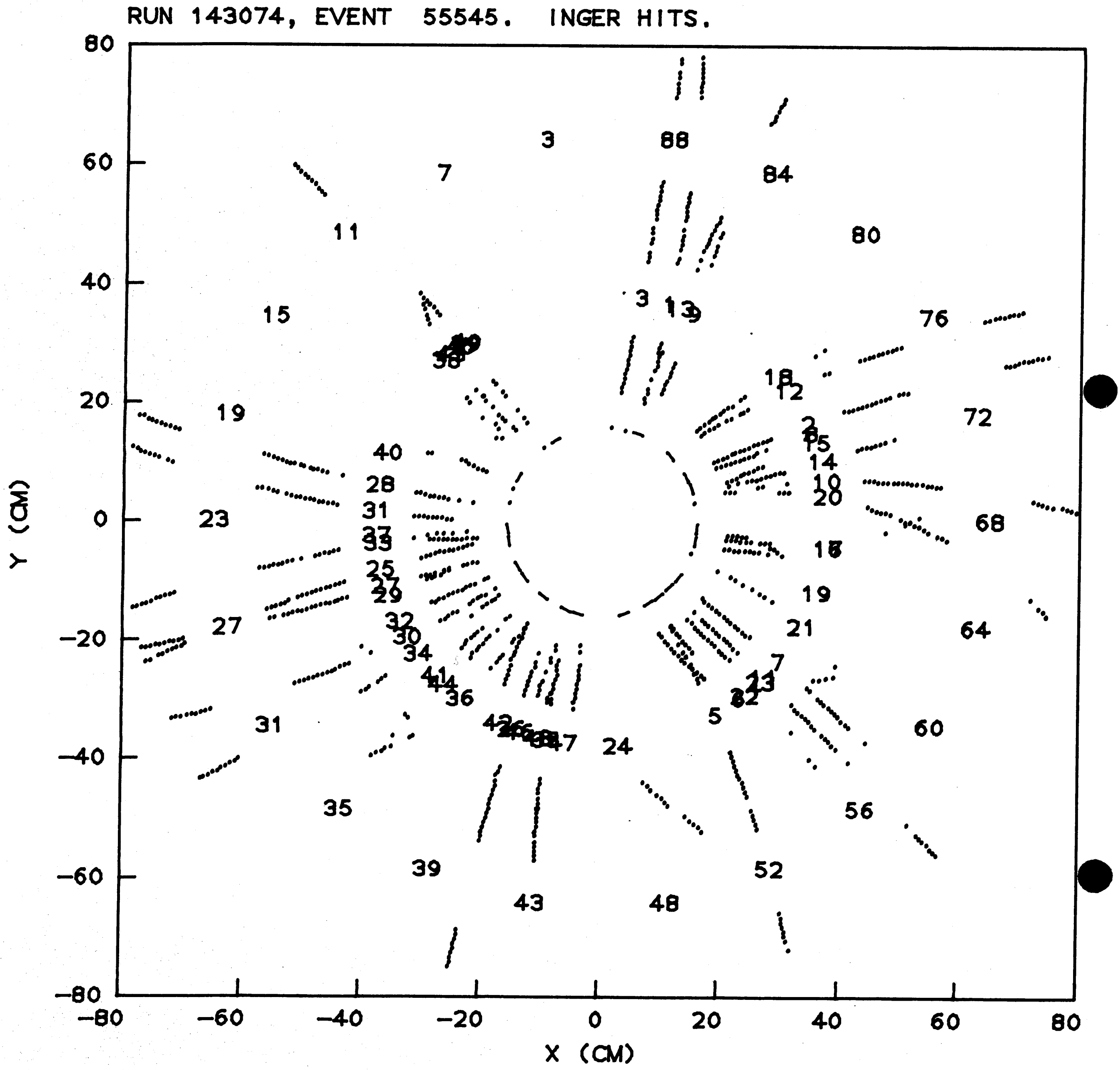

Fe / LA
10 GeV/c π⁻
INTERACTION IN SECOND SECTION
CHARGE SUM
Counts
800
400
0
10
20
30
40
50
60
70
channels
U238 / LA
10 GeV/c π⁻
INTERACTION IN SECOND SECTION
CHARGE SUM
SAMPLING UNFOLDED
Counts
1000
500
0
10
20
30
40
50
60
70
channels

Fig. 5


RUN 143074, EVENT 55545. INGER HITS.
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X (CM)
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60
40
20
0
−20
−40
−60
−80
−80
−60
−40
−20
0
20
40
60
80

Fig. 6