FEATURES OF EXPERIMENTS AT ENERGIES ABOVE 1 TeV

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1. INTRODUCTION

One can hope that, in the not very distant future, physicists will have the opportunity to work at accelerators in the TeV energy range. Striving for still higher energies is natural, but in this case one should meditate on how much the energy growth corresponds to potentialities of the experimental technique. The present paper is aimed to the discussion of the problem of particle detection at 2 to 5 TeV proton accelerators.

Before taking up this subject, it is useful to formulate briefly the main trends of experimental research for the TeV energy range. Recent years are remarkable for tremendous progress in high energy physics. Among the most important discoveries, we should note the growth of the total cross sections, the scale invariance phenomenon, and discovery of neutral currents, of a heavy lepton and of a family of particles with new quantum numbers. The bulk of the experimental data at present and the efforts of theoreticians have made more profound our understanding of elementary particle structure and their interactions. Realistic renormalizable models of weak interactions have been put forward, and they unified weak interactions with electro-magnetic ones thus stating a fundamental fact on the unity of these forces of nature. Great progress in the development of quark models brought us to a new level of understanding of the nature of strong interactions.

Future experiments at even higher energies will allow us to check the modern notions, to develop them further, and to clarify the details.

Elementary particle theory is based on quantum field theory, whose fundamental principles are causality, relativistic invariance, and unitarity. Just from these principles there follow dispersion relations, as well as a number of asymptotic theorems that put limitations on the behavior of both elastic and inclusive processes at high energies. Consequently, the higher the energies the more possibilities we have to check the basic principles of the theory. For instance, deviations from the predictions would be evidence of the existence of an elementary length, which might crucially change the principles of the theory. Hence the modern level of elementary particle physics raises a number of long-term physical problems that demand experimental study and determine our choice of the main trends in investigations to be carried out at a proton accelerator with the energy of about some TeV. These are as follows:

a) search for and detailed study of hadrons containing heavy quarks (in this case both the study of states with the known quarks (c, b) and with the suspected ones (for example, t-quarks) is implied. An important circumstance in the transition to high energies is not only an increase of the mass range accessible but an increase in the particle production cross sections, as well as the relativistic growth of their life-time in the lab system;

b) search for heavy leptons, the study of their decays and production mechanisms;

c) at TeV energies, there exists an essentially extended opportunity to search for objects of a new type, such as free quarks and color states, Higgs bosons, intermediate vector bosons, exotic (from the viewpoint of the quark model) systems, for example, bound states of a few gluons (glueballs), multiquark bound states, etc.;

d) the high energy neutrino interaction will make it possible to study the structure of weak currents and may become a source of intermediate bosons. A detailed study of neutrino interactions will enable us to judge on the presence of intermediate bosons even in the case of their mass exceeding 50 GeV. Intense beams of polarized muons will also assist the study of high energy weak interaction effects;

e) to define more accurately the structure of hadrons, and the dynamics of quark-gluon interaction at small and large distances, a wide scope of research is necessary to be carried out. This includes:

- the study of multiparticle processes with a large momentum transfer in hadron-hadron collisions, the study of the composition of hadron jets;
- the study of two-particle and quasi two-particle processes with a large transverse momentum, those in charge exchange reactions included;
- the study of the phenomenon of the total cross section growth; the study of the characteristics of inclusive processes;

f) the study of lepton-hadron deep inelastic interactions in a wide energy range; the study of leptonic pair production in hadron collisions.

The experiments which are necessary to be carried out in the energy range exceeding 1 TeV in order to solve these problems require complicated facilities to be created, and the development and perfection of particle detection methods. Below we shall discuss the features of the superhigh energy experimental technique. Neutrino experiments requiring complex facilities will be considered separately.

2. EXPERIMENTAL TECHNIQUE

a) Particle Identification

The problem of selecting particles of different masses is often faced both in identifying the components of beams and in identifying secondaries produced in the setup target.

The former problem is solved more easily despite the fact that the beam particles have far larger momenta than the secondaries. That this is so is related to the fact that in the former case single particles having small angular divergence and momentum spread are identified. The presently existing technique of Cherenkov counters allows us to select beam particles of a given sort in the energy range up to a few TeV. On the other hand, the difficulties in identifying the secondaries with their high multiplicity, large angular divergence and wide momentum spectrum will be rather great and will call for an essential development of the experimental methods, at least in quantitative respect.

Cherenkov Counters

A gas threshold Cherenkov counter is the simplest Cherenkov detector to identify superhigh energy particles. The Cherenkov counter length necessary to separate the beam particles grows proportionally to E^2. At $E \simeq 1$ TeV, it reaches 1÷2 km if pions and kaons are to be separated.

To select particles in a differential Cherenkov counter the dependence of Cherenkov radiation angle on the velocity is used. The resolution of a differential Cherenkov counter is improved with a decrease in the angle of Cherenkov radiation and optic system, angular spread of beam particles, and multiple scattering in the counter matter. To achieve a good velocity resolution, the radiation angle has to be reduced, yet the number of photoelectrons must be sufficiently large to gain the detection efficiency required. Under the condition that the main contribution to the resolution is determined by the dispersion of the refractive index in gas (i.e., in well collimated beams with angular spread less than 10^{-6}) a counter about 200 m long with dispersion compensating optics is sufficient to separate E = 3 TeV kaons and pions.

Recently, the application of Cherenkov counters for measurement of the velocities and angles of a few particles at a time has started. As to their principle of operation, they are similar to differential ones, yet with a significant difference in that instead of a diaphragm selecting light emitted in a definite angular interval, they employ a system of PMs to measure the Cherenkov radiation angle. The Cherenkov light is detected by a large number of small-scale PMs or special PMs that permit the identification of the point at which light strikes the photocathode. The velocity resolution of 10 m long counters of this type is $3 \cdot 10^{-6}$; this makes it possible to separate pions and kaons of an energy up to 150 GeV. The basic novel feature of this counter is an option of simultaneous detection of a few particles.

Transition Radiation Detectors

The velocity of ultrarelativistic particles can be measured with the help of the transition radiation at the interface between two media. This radiation has a strong directivity, $1/\gamma$, its intensity grows linearly with γ, and the characteristic energy of γ-quanta used for detection is about 1 KeV. Since about 10^{-2} photons are emitted at one interface, this makes it imperative to employ a radiator consisting of about 10^3 foils. To form transition radiation each foil has to be sufficiently thick ($\simeq$ 0.03 mm), in which case the total thickness of the radiator matter will amount to $\simeq$ 3 cm. Materials with the minimal Z are to be used to avoid photon absorption. To detect γ-quanta xenon-filled proportional chambers or other detectors of X-ray radiation are used.

A detector of this type is actually a threshold device because the cross section for photon absorption shows a sharp increase with a decrease in their energy (for example, if a lithium foil radiator is used, only particles with $\gamma > 2 \cdot 10^3$ are detected). To achieve spatial separation of the transition energy photons and the particle itself, use is made of the natural divergence of transition radiation or of particle deflection in the magnetic field. This technique is gradually becoming available in practical form in physics experiments.

Detectors of Synchrotron Radiation

An electron passing through a magnetic field emits energy $\propto E^2B^2$. Thus, an $E = 0.1$ TeV electron which has transversed 5 m of 20 kG magnetic field will emit 20 photons of 10 MeV energy. This radiation can be detected in a fairly simple way by means of conventional counters. Application of synchrotron radiation has prospects for future electron beams in proton accelerators.

Ionization Measurements

The measurement of ionization losses in the region of relativistic rise enables us to identify charged particles (pions, kaons, protons) in the 5-100 GeV/c momentum range. Above this energy ionization losses reach a plateau due to the density effect. The difference in losses for particles of various masses is small, $\simeq$ 10%, therefore the detector should have a high energy resolution. Besides, due to large fluctuations of ionization loss, multiple measurements are necessary to determine the primary ionization. Gas gaps of each sampling should be at least 5 cm thick so that the measurement at each point on the track can have a low statistical fluctuation and the number of samples should be about 150. Early detectors of this type have recently been tested successfully.

Time-of-Flight Measurements

The difference in time-of-flight on the base L of particles with masses M_1 and M_2 equals $(M_1^2 - M_2^2) \cdot L/2E^2c$ (note that for this technique $L \sim E^2$). For antiprotons and antideuterons the difference is, for instance, $2\ 10^{-11}$ sec on a 1 km long base with $E = 0.5$ TeV. Presently existing scintillation counters have a time resolution down to 10^{-10} sec, which is an actual limit for a scintillator-PM system. In parallel-plane spark counters comprising one semiconductor, time resolution less than 10^{-10} sec can be achieved. Such detectors can be applied for detection of comparatively slow secondaries.

b) The Measurements of Charged Particle Coordinates and Momenta.

To determine the momentum of a particle above 1 TeV an improvement in the accuracy of measuring its trajectory upon deflection in a magnetic field is necessary. In this case the limited possibilities to increase both the value of the magnetic field and the path length of the particle traversing it are to be considered. Below we shall discuss the capabilities of two types of track detectors mostly used nowadays.

Drift Chambers

The basic advantage of these detectors is a small number of signal channels per unit of area and their high spatial resolution (better than 0.1 mm). The counting rate for short lengths of signal wires is constrained by space charge and for large lengths by the signal duration at the amplifier input, and, as a result, by a flux of up to 10^6 part/sec per wire (a typical wire spacing in drift chambers is 10 cm). With large drift spacings one should also take into account the drift time imposing additional limitations on the admissible count. The presently achieved accuracy of measuring the coordinates in drift chambers can be improved to $\simeq$ 0.05 mm.

At present these chambers are an optimal detector in cases when large areas (tens of square meters) are necessary to be covered and particle fluxes do not exceed 10^5 part/sec per wire.

Proportional Chambers

A typical spacing of signal wires in a proportional chamber is 2 mm. Therefore 50 times as much particle flux can enter a proportional chamber as compared to a drift chamber. There are possible further improvements of wire chambers, which will probably make their counting rate still higher.

The accuracy of particle track localization in proportional chambers is $\simeq$ 0.3 mm in a conventional operating mode. With read-out of an induced signal, accuracies better than 0.1 mm are achieved. However, in this case there appear difficulties in making big chambers.

The space resolution of gas coordinate detectors is limitted by appearance of delta-electrons resulting in the center of gravity of an electric pulse biased with respect to the particle trajectory. This value lies in the range of 0.01 mm, which seems to be the limit for gas detectors.

The aforementioned accuracies of coordinate measurements are sufficient for comparatively precise measurements of particle momenta with the help of a standard method of magnetic analysis. This method will still be basic at a 2-5 TeV energy accelerator as well. With reasonable lengths of magnetic path (tens of meters) and a 100 m deflection basis, the momenta of the highest energy particles will be measured with an accuracy better than 1% (yet, one should keep in mind that 1% of 5 TeV is 50 GeV).

c) γ-Quantum Detectors. Calorimeters.

For measuring particle energies and coordinates, particular importance will be attached to calorimeters. With an increase in the collision energy the multiplicity of secondaries is rising, the final states contain tens of particles, and π^0 mesons and other particles decaying into γ-quanta make up one-third of them. Therefore a systematic study of interactions in this energy range is impossible without devices simultaneously detecting a great number of γ-quanta. A promising technique using a Cherenkov counter hodoscope has recently been developed, which provides an opportunity to carry out highly accurate simultaneous measurements of the coordinates and energies of a large number of γ-quanta and reconstruct masses and coordinates of the decay particles. The accuracy of these detectors is improved with energy, $\sim 1/\sqrt{E}$, and at 2 TeV it will be: $\Delta E/E < 1\%$, $\Delta X < 1$ mm, $\Delta M/M < 1\%$.

The calorimeter dimensions are determined by the shower length and have only a logarithmic growth with energy. This is a most important advantage of calorimeters, which makes them the basic instruments at energies above 1 TeV. They will play an important role also in detection of hadrons. In this case, a conventional device will be a sandwich comprising an array of heavy plates, whose total thickness will be about 10 collision lengths. A scintillator, liquid argon, or a high pressure inert gas can be used as an ionization detecting medium. If uranium plates are employed, this detector will be 1-2 m long, the energy resolution for 2 TeV hadrons will be a few percent, and the space resolution (providing a detector of a hodoscope type is used) will be better than 1 cm.

The counting rate limit of a calorimeter utilizing a sufficiently fast-operating scintillator is determined by delayed radiation (neutrons from nuclei) and is dependent on the detection threshold. If the threshold is a few GeV, such a detector will be able to operate in a flux of 10^7 pps.

d) Detectors of Short-Living States.

In recent years search for particles with a life-time of

10^{-13}-10^{-14} sec has resulted in an acute necessity for detectors to examine particles with a range of 0.01-0.1 mm prior to decay. For these purposes, photoemulsions are being used, in conjunction with electronic methods which identify particles and localize the interaction point in order to reduce the volume of scanning. This technique will also be improved in the future, but decisive progress in this direction is connected with the development of methods of electronic detection of short-lived states.

To solve this problem a great number of detectors is being developed at the moment. These include:

- high pressure streamer chambers;
- streamer chambers with detection of laser light scattered on the ionization centers;
- liquid argon ionization chambers with very narrow ($\simeq$0.01 mm) strip electrodes;
- liquid chambers with ionization transfer into gas for further amplification and detection;
- electroluminescent detectors;
- solid detectors with high space resolution.

The development of techniques in this direction may prove to be useful in solving other experimental problems.

3. NEUTRINO EXPERIMENTS

a) Neutrino Beams

The two types of neutrino beams used in the presently existing accelerators (wide band and narrow band beams) will also be used in superhigh energy accelerators. Though the highest energy region will become most interesting for neutrino research, the low energy one, where the maximal neutrino flüxes are achieved, will also be important for a long period of time. At superhigh energies the idea of tagging neutrinos in specialized neutrino beams (dichromatic beams of muonic neutrinos) will probably become possible. Tagging will allow a more precise measurement of neutrino energy and will avoid ambiguity (pion or kaon neutrinos). However, the problem of tagging is rather complicated due to a high level of detector loading (more than 10^8 muons per cycle).

Beams of electron neutrinos will also be of great interest. Electron neutrinos (less than 1%) present in usual beams of muonic neutrinos are scarcely suitable for a detailed study of their interaction. A sufficiently pure beam of ν_e from K decay ($\nu_e/\nu_M = 1.4 : 1$) can be obtained by forming a neutrino beam from a neutral one.

b) Neutrino Detectors

Bubble Chambers

With an increase in the energy and intensity of neutrino beams a "pure" bubble chamber looses its capabilities as an efficient instrument. At the already achieved neutrino energies there arose a necessity to equip the big existing chambers with peripheral identifiers of particles. With further increase of the accelerator energy by an order of magnitude, the momenta of highest energy particles will be practically unmeasurable. Particles produced in neutrino-nucleon interactions lies within a very narrow cone; this does not allow one to identify and to separate them spatially. However, bubble chambers will remain as long-term instruments for vertex detection in combined systems (see below).

Detectors of Calorimeter Type

Neutrino detectors based on a hadron calorimeter and a muon spectrometer made of magnetized iron are rather promising at superhigh energies. In such detectors, separate hadrons cannot be detected, but the energy of the hadron system is measured with a good accuracy ($\sim 1/\sqrt{E}$ (see above), i.e., a few percent). With a calorimeter containing track detectors there is the possibility of determining the neutrino interaction vertex, the muon angle, and the direction of the total momentum of hadrons (with an accuracy $\simeq 1/E$ (TeV), mrad).

Identification of muons and measurement of their energies in the 1-10 TeV range remains possible by using conventional (for neutrino experiments) magnets made of magnetized steel (about 20 m long). In this magnet, the sagitta of a 2 TeV muon will amount to 15 mm, and the measuring accuracy of a muon is basically determined by multiple scattering.

A possible version of the experimental setup to study neutrino interactions in the TeV energy range is a $\simeq$ 20 m long iron-filled calorimeter (about 1,000 tons) followed by a muon spectrometer. The research quality of high energy neutrino interactions will be noticeably higher owing to an improvement of the energy resolution for hadrons and muons. While studying deep inelastic neutrino scattering, it will be possible to ensure an appreciably better accuracy in measuring the variables X and Y. The study of processes with production of a few muons at superhigh energies is more promising because backgrounds from pion and kaon decays will decrease with energy. In a detector of this type one can find an intermediate W-boson (from $\mu^+\mu^-$ events in a neutrino beam without energy release into hadrons).

To carry out experiments with electron neutrinos at superhigh energies a calorimeter detector is necessary, which can efficiently separate electromagnetic showers from hadronic ones and is also sensitive to the muonic component from muon neutrino interactions in the detector. Such a detector can, for example, consist of sections of a scintillator alternated with those of heavy shower detectors.

Hybrid Detectors

A hybrid detector which is a combination of nuclear emulsion target and a magnetic spectrometer can be used in wide band neutrino beams. Particle momenta are measured and coordinates inside the nuclear stacks predicted with the help of track detectors, which are a part of the spectrometer. Usage of additional detectors, i.e., hadron calorimeter, shower detectors and muon identifier, will allow the identification of secondary particles. Such a combined facility will enable, for example, a search for new short-lived particles.

Finally, a hybrid detector with a bubble chamber as a target and external electron detectors is a promising facility to study neutrino interactions at superhigh energies. Such a detector is capable of providing complete information on each neutrino event. However, the existing big bubble chambers having too much matter in the path of secondaries (chamber walls, magnet windings) will have to be modified, otherwise particle identification is difficult.

4. CONCLUSION

Above we have attempted to analyse briefly the features of experimental setups in the TeV energy range. We were interested mainly in whether this great step in the energy range, as opposed to that already handled by physicists, will lead to the necessity of a new approach in experimental methods and will require particle detectors of a new type. As shown in this survey, present day methods permit successful detection and identification of particles in the TeV range. The main difficulty lies in a new level of requirements imposed on physics research rather than in high energy itself.

A successful solution of the experimental problems will require the creation of very big facilities. Their information collection capability will become far larger at the cost of increase in the number of detecting elements (the number of wires in the chambers, counters, amplifier channels, etc.) as well as due to detectors of different types applied in one installation. Within the decade separating us from constructing accelerators of the next generation, experimental techniques will be developed significantly and undoubtedly they will not slow down experimental advance in high energy physics.

Table 1.

a) Particle Identification Methods

Type of Detector	Energy Range for π and K Identification	Principle Formulas	Notes
Threshold Cerenkov counter	$P < 1$ TeV	$\ell \sim E^2$	$\ell = 1$ km
Differential Cerenkov counter	$P < 3$ TeV	$\ell \sim E^2$	$\ell = 200$ m $\Delta\theta < 10^{-6}$
Multicell Cerenkov counter	$P < 0.2$ TeV	$\ell \sim E^2$	$\ell \simeq 20$ m can measure the velocity of several particles.
Transition radiation	$P > 0.2$ TeV	$n_\gamma \sim \gamma$	The required path is $\simeq 10$ m, 2g of material on particle trajectory.
Ionization measurements	0.005 TeV $< P < 0.2$ TeV	$I \sim \ell n\gamma$	$\ell \simeq 10$ m
Synchrotron radiation	$P > 10$ eV	$E_\gamma \sim E^2B^2$	Only for electrons.

b) Particle Energy Measurements

Device	Parameters	ΔX	$\Delta\theta$	ΔP for 1 TeV
Magnetic Spectrometer	$B \times L = 10T \times m$ path $\simeq 20$ m	0.1 mm	10^{-5}	$\frac{\Delta P}{P} \sim P$ $\frac{\Delta P}{P} \simeq 0.5\%$
Lead-Glass detector	$\ell \simeq 1$ m path $\simeq 100$ m	1 mm	10^{-5}	$\frac{\Delta P}{P} \sim 1/\sqrt{P}$ $\frac{\Delta P}{P} \simeq 0.5\%$
Hadronic calorimeter	$\ell \simeq 2$ m path $\simeq 100$ m	10 mm	10^{-4}	$\frac{\Delta P}{P} \sim 1/\sqrt{P}$ $\frac{\Delta P}{P} \simeq 2\%$