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PROPOSAL FOR A SEARCH FOR NEW PARTICLES AT THE ISR

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1. Introduction

In mid-1971 both the ISR at CERN and the 500-GeV synchrotron at NAL are scheduled to be ready for beam tests and, hopefully, shortly thereafter for physics experiments. Undoubtedly one of the first experiments to be performed at NAL will be a search for quarks. In fact three of the first 76 proposals to NAL specifically mention quarks in their titles.1) For CERN it would be a great pity if quarks were first discovered at NAL. Even though quark production might just be above threshold at NAL, the much higher intensity of that machine would mean that all interesting experiments with quarks, apart perhaps from studies of the production process, would be performed at NAL.

The fundamental question of the existence of more basic constituents of matter than the elementary particles we know, the strong competition from NAL in time-scale and in its predictible first emphasis on quark searches, and the potentiality of a whole new field of physics, would seem to make it imperative that at least one of the first of several experiments at the ISR should be devoted primarily to a search for new particles. The present proposal is for such an experiment.

We are well aware that quarks, as physical objects, possibly do not exist. Many experiments have been performed to look for them both with cosmic rays and with accelerators. Another class of experiments have looked for fractionally-charged stable particles which may have accumulated on the earth. The results of these experiments have for the most part been negative. There are however some pieces of evidence, which may or may not be reliable, for peculiar effects at high cosmic ray energies. Some of these effects may possibly be attributed to quark production.[2)]

From the theoretical point of view, there is some reluctance to believe in the existence of quarks as physical objects. Even though the quark model has had and continues to have great success in many areas, the problems of understanding how quarks are bound to make up the particles we know seem to be insurmountable to some theorists. Nevertheless, the quark model suggests that the nucleons do have structure. Moreover the parton and similar models, invoked to explain the deep inelastic electron scattering results, suggest that structure exists. On the whole, there is considerable impetus for looking for (probably) heavy particles which may be the fundamental constituents of nucleons. We should be prepared for any possibility. Although the first suggestion of composite structure introduced the triplet of fractionally-charged quarks, any constituent particles which we may produce may have completely different properties.

We would justify a careful search for new particles on the following grounds (not necessarily listed in order of relative importance):

1. The possible discovery of a new class of elementary objects would be one of the most important contributions to physics.

2. In view of the considerable effort already expended in quark searches, it is reasonable to extend the search using the ISR. The ISR constitute the best potential source of constituent particles in the forseeable future because they have a c.m.

energy twice as high as NAL, and an intensity much larger than that of cosmic rays.

3. Without doubt, a quark search will be high on the list of priorities at NAL. It is imperative that the ISR be in a strongly competitive position, even though it may turn out that NAL is below threshold for the production of possible new constituent particles.

4. A major justification for building the ISR is that they open up a completely new energy region where new phenomena are to be expected. Searches for new and unconventional phenomena should be undertaken.

We are not so naive as to believe that other groups have not also thought about quarks. It may be that some of them have plans for quarks searches which have not been outlined in their proposals. If quarks are produced copiously at the ISR, they may well be detected by one or more of the groups with already approved experiments. On the other hand, they might well be missed if, for example, they are not fractionally charged. In any case, these groups are committed to the measurement of other things - any search for quarks would seem to be a spare-time activity or a by-product. We feel that at least one of the first several ISR experiments should be devoted solely to a systematic search for new particles, with no other commitments.

A possible alternative is that several of the existing groups spend a considerable fraction of the first operational time of the ISR on a search for new particles. This may make sense if they turn out to be easy to find. However, we feel that this may result in other important measurements being neglected. Also, what we propose is a careful, systematic search with dedication, and with the latest state-of-the-art capabilities of the apparatus.

Undoubtedly a system of apparatus designed to look for new particles can make measurements of other quantities as well. However, we will not discuss this possibility here - it should only be considered if a diligent search proves unfruitful.

2. Production Cross Sections

Estimates of quark production cross sections based on the statistical or thermodynamical model of particle production make the ISR look unattractive as a source of quarks³⁾. Massam and Zichichi⁴⁾ proposed that 1 event in 10 days with 4π solid angle seemed like a realistic limit for detection, and this corresponds to a rate several orders of magnitude larger than what one would predict for massive quarks with the thermodynamical model.

There are suggestions both theoretical and from cosmic ray experiments that production cross sections are much larger. It is only on such a basis that an ISR experiment has a chance of success. Cross sections have been calculated by Maheshwari and Schonberg for the diffraction like process

$$\pi^{+} + p \rightarrow q + \bar{q} + p$$

under the assumptions of SU_3 and universality of the strong interactions⁵⁾. Their predictions range from 0.001 to 0.5 mb depending upon the values of their two parameters and the assumed quark mass.

Dooher[6)] has also estimated the cross section to be in the mb range for this process. The suggestion is that the process

$$p + p \rightarrow 3q + p \qquad (1)$$

may well have a larger cross section than

$$p + p \rightarrow p + p + q + \bar{q} \qquad (2)$$

at the same energy, even though the latter process has a substantially lower threshold. Of course, one should not take these predictions seriously in view of the many theoretical uncertainties. However, it is significant that these predictions are higher than typical statistical model predictions by some factor like 10^{30}!

Again, with regard to the cosmic ray experiments, there are only suggestions which may or may not be significant. However, although a single experimental indication may be rejected without qualm, it is more difficult to dismiss several anomalous experimental effects which can be tied together by the hypothesis that some new process, with a cross section in the mb range, appears at a lab energy of about 1000 GeV. We refer principally to the results of the Proton satellite series, as analysed and summarised by Kaufman and Mongan[2)]. We quote a particularly pertinent sentence from their paper: "The main problem with production mechanisms in general is that of the large cross sections necessary to match the experiments."

If we take the thermodynamical model predictions seriously, we should not even consider looking for heavy particles at the ISR - it would be hopeless. Now this model ignores any possible structure and treats quarks as just heavy particles like, for example, antideuterons, and to produce heavy particles in pp collisions is difficult. However, the Gell-Mann-Zweig hypothesis is that quarks are the <u>fundamental</u>

constituents of the proton.[7)] It is reasonable to suspect that, when you have enough energy, you can release them from their bound state with an appreciable probability. At this stage of our knowledge any other prediction for the production cross section can only be speculative. However, if quarks are the basic constituents of the proton, there is good reason to believe that they should be produced in a sizeable fraction of the interactions at high energies. This should also be true if the constituents are not the triplet quarks but something else.

It is also possible that the constituent particles, be they quarks, partons, or whatever, are not massive. It could be that a high energy is needed because we have to produce a large number of constituents, or because for some reason they can only be produced together with several pions.

3. Possible Charge States

In the Gell-Mann-Zweig model for quarks, the charges are (+2/3, -1/3, -1/3) for the p, n, and λ quarks respectively. For reaction (2), quarks of charge ±1/3 and ±2/3 can be produced. For reaction (1), two of the quarks have charge +2/3 and the other has -1/3. It has also been suggested that a quark-quark bound state might exist with charge +4/3. Thus, an experiment should be sensitive to charges ±1/3, ±2/3 and +4/3. These charge states have been searched for in most of the previous experiments with negative results.

It is well known that this scheme is not the only one possible. Lee has shown that there are several other possibilities[8)]. For his simplest example containing a triplet and a singlet, the charges would be 0 or ±1 for reaction (2) and 0,0, and +1 for reaction (1). Thus one has quarks with unit charge and a considerable fraction with zero charge. These are more difficult to identify than the fractionally-charged type, but should definitely be searched for. It could happen that the charged members of the triplet are unstable, and decay to the neutral member. The neutral singlet quarks have baryon number 1; that of the triplet quarks is not necessarily specified, but is likely to be 1/3.

So far as we know, the parton model has made no prediction for the charges of the partons.

The proposed experiment constitutes a search for fractionally-charged integrally-charged, and possibly later on, neutral particles. The apparatus has been specifically designed for these purposes and has several unique features which are outlined in the next two sections.

4. Design Considerations

Since the properties of constituent particles and any details of their production mechanisms are unknown, it is necessary to have some kind of model to guide the design of the experiment. We hope to allow for all possibilities in the proposed experiment. We will discuss here as an example quark production via the process $p + p \longrightarrow p + 3q$ and make some (which at present seem reasonable) assumptions about this process. From phase space considerations alone, the invariant mass X of the 3q system peaks at large values (35-45 GeV) for all assumed quark masses. However, we expect this to be damped by a factor like e^{bt} with $3 < b < 10$, and this results in somewhat lower values of X being favoured. It also means that 0-deg production of the 3q system is strongly favoured. Even so, quarks can come out at large angles. A plot of $-t_{min}$ (i.e. value of $-t$ for 0-deg production of the 3q system) vs. the invariant mass of the 3q system is shown in Fig. 1. Only for values of X greater than about 30 GeV does the exponential factor become important.

In Fig. 2 we show the invariant mass distribution of the 3q system, modified by the factor e^{10t}, and for a quark mass of 4 GeV. Fig. 3 shows the angular distribution of the quarks for X = 24 GeV, i.e. at roughly the peak of Fig. 2. Very similar results are obtained for other values of X (the angular distribution broadening for larger X) and for values of the quark mass from 1 to 12 GeV. Only if $M_q < 1$ GeV and $X < (3M_q + 1)$ GeV are the quarks confined to angles smaller than 10 deg. Although there may be another process in which quarks are produced at only very small angles, these considerations indicate that an angle of 5-10 deg is about optimum. It is also possible that the 3 quarks may be produced accompanied by several pions. If so, essentially the same results are obtained. The main difference is that the quarks tend to come out with lower momenta.

5. Experimental Setup

The apparatus which we propose to assemble at the ISR and which is sketched in Fig. 4 is not just another spectrometer, but is a mass spectrometer with some special features. The quadrupole doublet together with the two bending magnets bending in opposition provide a sizeable solid angle, a large momentum acceptance, two determinations of the momentum, and a fairly well defined beam at the focal plane of the system. This last feature permits measurements of the range and nuclear interactions of transmitted particles with apparatus of modest transverse dimensions.

Basically the mass is determined from the formula

$$M = \frac{p}{\beta}\sqrt{1 - \beta^2}$$

where

$$p = Zk(B\rho) \quad , \quad k = 0.3 \text{ GeV/c/Wb/m.}$$

The velocity β is determined for $\beta \leq 0.95$ from time-of-flight over about 20 m with a resolution of 1/3 nsec. For $\beta > 0.95$ the velocity is determined from pulse height in the Cerenkov counters. Once β is known, Z is determined from two or more independent measurements of dE/dx in proportional wire counters. The momentum is measured twice by the two bending magnets using 5 other proportional wire chambers. We use proportional rather than conventional wire chambers in the momentum determinations in order to be sensitive to particles of fractional charge.

For a central value of p/Z =10 GeV/c, the acceptance of the whole system is shown in Fig. 5. For the example of quark production of Figs. 2 and 3, we calculate that the efficiency for detecting a particular one of the three quarks at an angle of about 7 deg. is 4×10^{-4}. With the design ISR intensity, 1 event per day corresponds to a production cross section of about 7×10^{-6} mb. Of course, the efficiency depends upon assumed details of the production process, and upon the quark mass. For 12-GeV quarks the angular distribution is slightly narrower and the momentum distribution peaks at 7 GeV/c; an efficiency of 9×10^{-4} can be achieved by peaking the acceptance at about 5 GeV/c.

For integral charges the mass resolution is

$$\frac{\delta M}{M} = \left[\left(\frac{\delta p}{p}\right)^2 + \left(\frac{\delta \beta}{\beta}\right)^2 \frac{1}{(1-\beta^2)^2} \right]^{\frac{1}{2}} \quad .$$

For fixed settings of the magnets (say at 10 GeV/c) $\delta p/p$ increases linearly with momentum, reaching 2% at 20 GeV/c. The contribution to the mass resolution from the second term is less than 0.02 up to $\beta \approx 0.9$. For $\beta \gtrsim 0.95$, measurement of pulse height in one of the Cerenkov counters gives $\delta\beta \approx 5 \times 10^{-4}$ and a mass resolution of a few percent. For fractional charges the resolution at a given momentum scales essentially inversely with the charge.

The box R at the end of the system in Fig. 4 is used to observe what happens to particles as they are brought to rest by nuclear and electromagnetic collisions. It incorporates absorbers, scintillation counters and proportional chambers. The first 100 g cm^{-2} is used to measure the shape of the range curve, and for particles with $M\beta^4/Z^2 \lesssim 1/4$ GeV the range can be measured. The main bulk is designed similarly to a total absorption spectrometer or calorimeter$^{9)}$. Measurement of range provides an over determination of the mass; measurement of the nuclear interactions may be expected to give the baryon number of any anomalous objects$^{2,6)}$.

The whole system will have the capability of measuring more than one particle coming through at a time, although in general this is expected to occur only occasionally.

6. Other Considerations

We feel that this proposed experiment to search for new particles should be one of the first scheduled at the ISR. However, we expect realistically that we could be ready from June or July, 1971. We will need 3-6 weeks in a test beam going up to about 15 GeV/c at the PS in order to obtain precise calibration curves for all components of the mass spectrometer. At the ISR three different settings of the magnets for each polarity will permit a detailed investigation of the mass and charge spectrum.

We wish to reiterate that the proposed apparatus has a sizeable solid angle and a large momentum acceptance with a typical mass resolution of ±2%. Perhaps more importantly it provides a reasonable beam for the investigation of the properties of new particles if they are found.

At a later date we may propose to look also for new neutral particles. A scheme for this is to place scintillators in the vicinity of the intersection to obtain a time zero signal, and to move the range/calorimeter down into the undeflected beam and measure details of the nuclear interactions as a function of velocity.

References

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Figure Captions

Fig. 1. Plot of $-t_{min}$ *vs.* the invariant mass of the (3q) system for the reaction $p + p \rightarrow p + (3q)$ at $E_1 = E_2 = 25$ GeV.

Fig. 2. Invariant mass spectrum of the (3q) system modified by the factor exp(10t) for a quark mass of 4 GeV.

Fig. 3. Angular distribution of 4-GeV quarks from the reaction $p + p \rightarrow p + 3q$ calculated from phase space modified by the factor exp(10t).

Fig. 4. Experimental layout for a search for new charged particles at the ISR.

Fig. 5. Solid angle acceptance of the proposed spectrometer for a central momentum of 10 GeV/c.

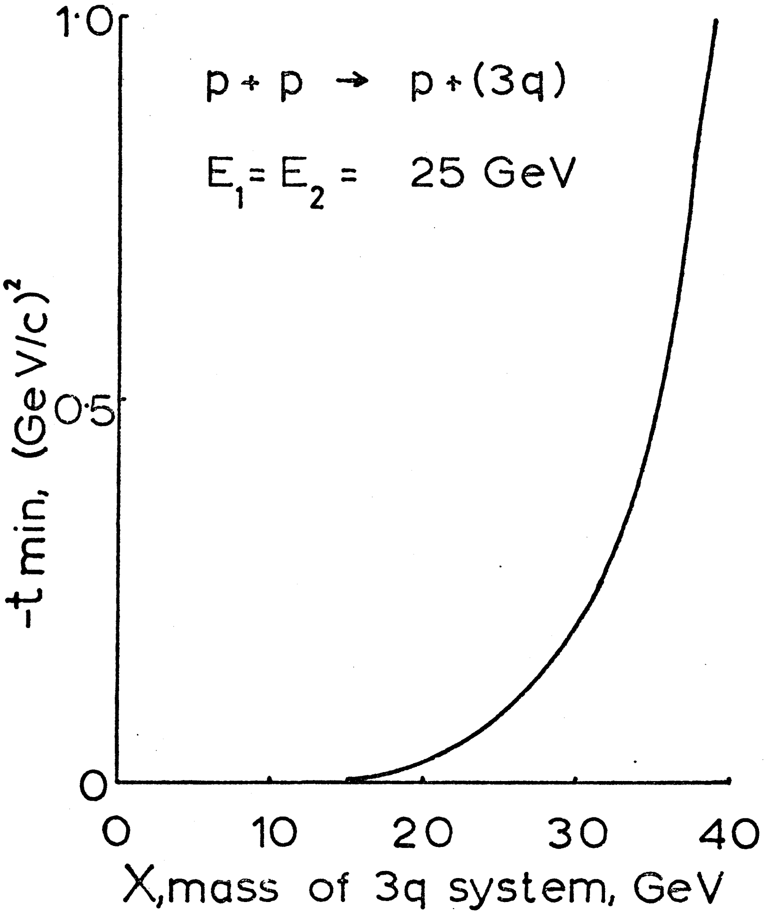
1·0
0·5
0
-t min, (GeV/c)^2
$p + p \rightarrow p + (3q)$
$E_1 = E_2 =$ 25 GeV
0
10
20
30
40
X, mass of 3q system, GeV

Fig.1

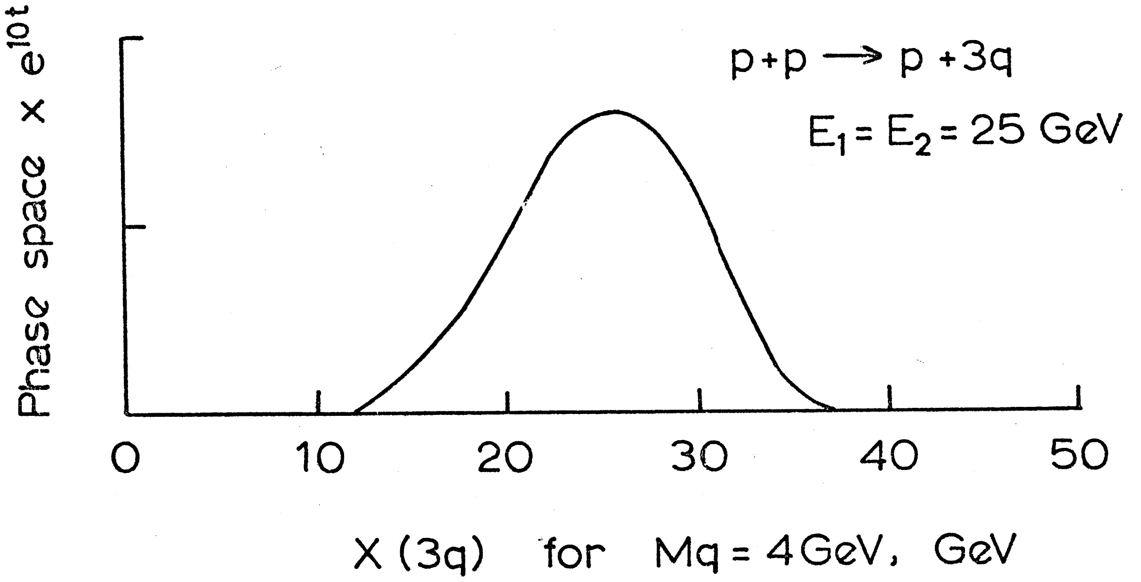
Phase space x e^{10t}
$p+p \longrightarrow p+3q$
$E_1 = E_2 = 25$ GeV
0
10
20
30
40
50
X (3q) for Mq = 4GeV, GeV

Fig. 2

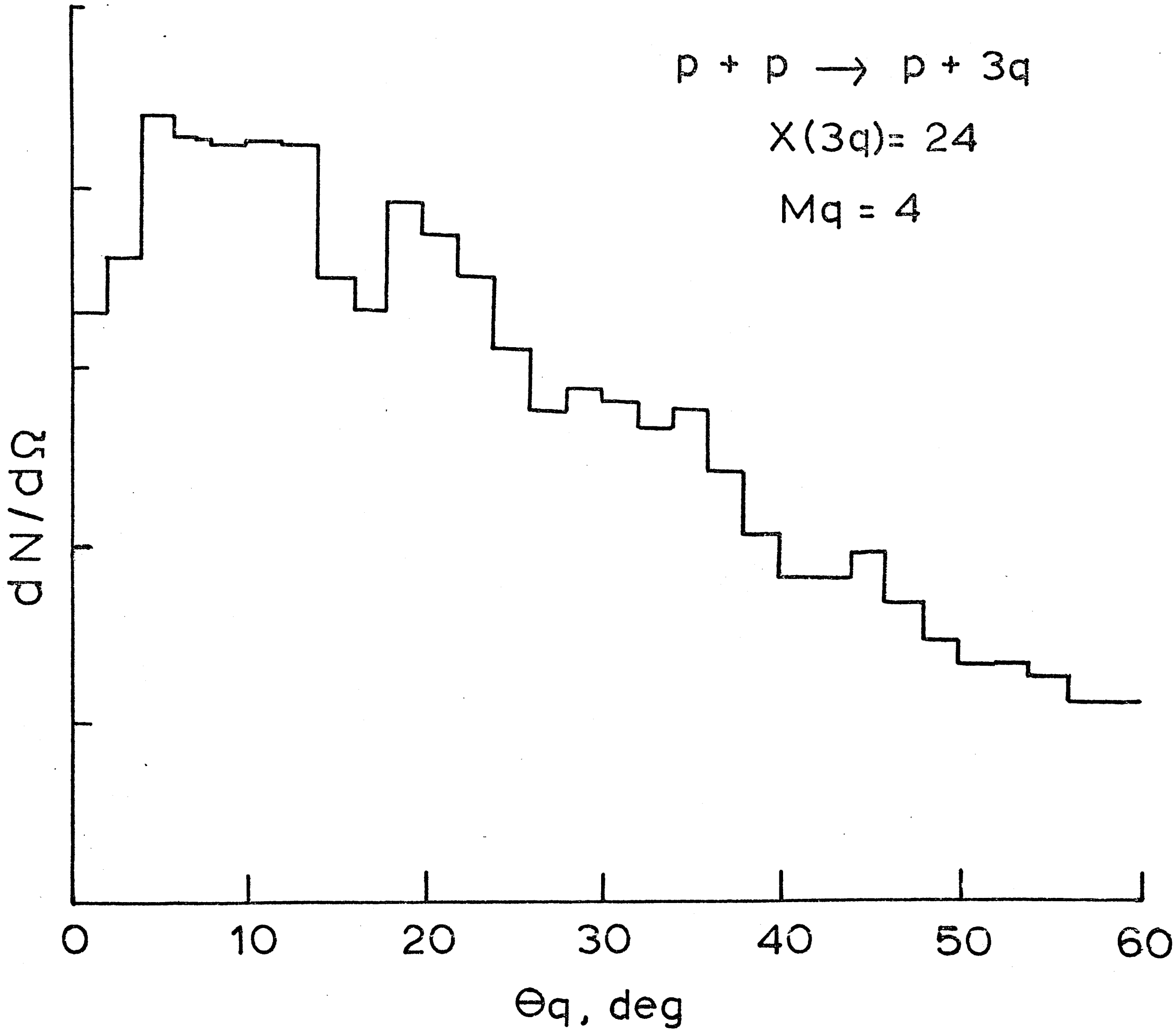

Fig. 3.

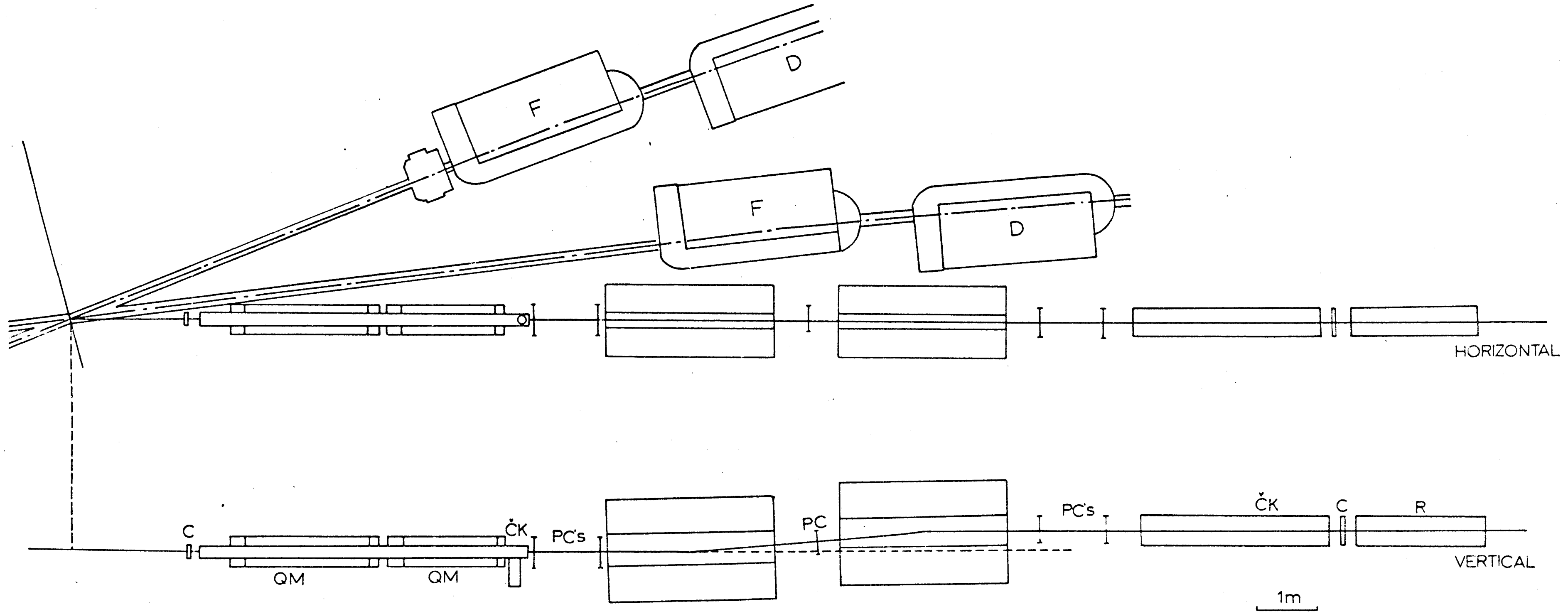

Fig 4

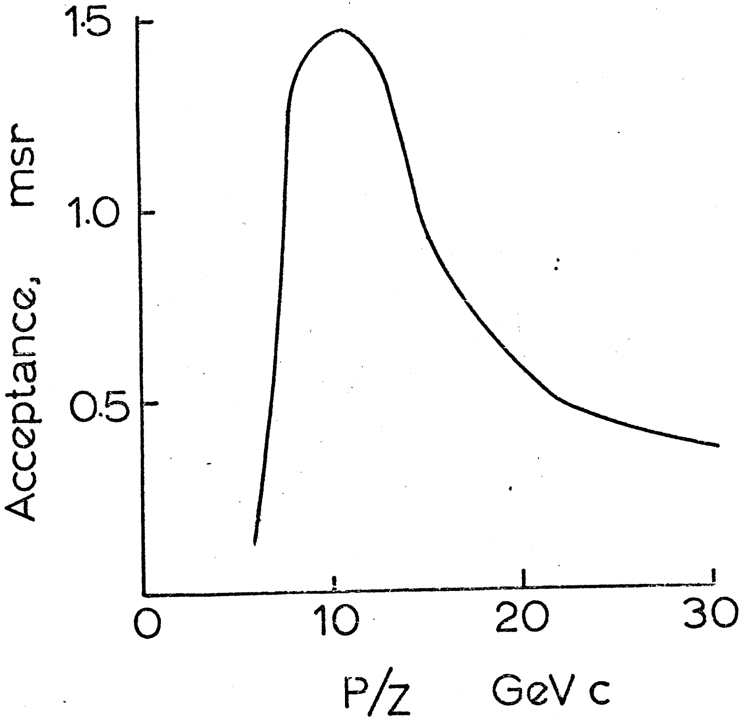

Fig. 5