THE ALPHA PROJECT

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ABSTRACT

Capabilities and magnet cost are examined for a large magnet used as a single vertex-surrounding analysis device with streamer or wire chambers or similar detector elements. For a magnet of 5 m diameter, 30 kG, comprehensive 4π detection capability can be obtained, together with momentum precision better than 0.1 BeV/c with practical additional downstream measurement. The cost of such a magnet has been estimated to be about \$3 million.

I. REQUIREMENTS FOR HADRON EXPERIMENTS

Among the many experiments with hadron beams that have been proposed and examined in the NAL Summer Studies, a considerable number have a common characteristic, namely that a large magnetic field or fields, with $\int B d\ell \sim 150$ to 250 kG-m, is used to measure high momentum particles with high momentum accuracy. The typical aperture is of the order of 1 m^2, although for some specialized experiments an aperture of several times smaller cross section is suggested.

Several experiment designs involve "vertex chambers" to identify specific multiparticle states. One approach to a device of this kind is the hybrid chamber system, explored extensively in the 1968 Summer Study.[1-3] Several experiments examined in 1969 also require vertex chambers (Anderson,[4] Gittelman,[5] and Osborne[6]). The vertex chamber (or in the original hybrid design the vertex chamber and the 5 - 20 GeV/c magnet together) also typically requires a magnetic field of several cubic meters volume, at 20 - 30 kG.

When one considers the virtues of various possible arrangements involving "vertex" and "spectrometer" magnets of the above sizes, one finds a number of powerful arguments in favor of combining the vertex and spectrometer parts of the field into a single field region, with $\int B d\ell \sim 150$ kG-m. It is the purpose of this note to list and review the major arguments suggesting such a single-field system and the rough performance and cost figures associated with it.

We summarize briefly some specific size, performance, and cost characteristics of a suitable magnet. In the next section we indicate the measurement accuracy obtainable and how it leads to the size requirements. A suitable magnet might be LWH = $1 \times 1 \times 6$ m, 20 kG; using the crude cost figure of \$5 K/cu ft, such a magnet would cost about \$1 million. The $\int B d\ell$ value of this field (actually it is BL^2 that is more appropriate for many purposes) is adequate, for experiments up to at least 100 GeV/c, as explained below, but the aperture is a little small for many purposes. One would like a larger aperture at the downstream end in order to allow better exiting of high momentum particles and of π^0's into particle identifying apparatus, and one would like larger aperture around the target at the upstream end in order to provide better detection and measurement of lower-momentum charged and neutral particles. An aperture of 1.5 m $\times$ 1.5 m is more suitable. Such a magnet might cost \$2 million.

Detectors and Optical Access

One must ask what kind of detection system would be used inside this magnet. At present, the competitors are optical chambers, wire chambers, and streamer chambers. For two of these, one must be able to see into the field region. If one therefore considers a pole-free magnet, one is then dealing with an arrangement where the vertical dimension is not critical. John Stekly* has made a rough estimate of the cost of a magnet (iron-free) with diameter 5 m and central field of 30 kG; the field strength in that magnet would be very uniform axially to a few percent over a height of 1.5 meters. The cost of such a magnet would be about \$3 million. Stekly estimates that within 0.75 m in any direction from the central point, the field strength should not vary more than 2 or 3 percent; at the edges of the 5 m diameter the field might be down as much as 10%. This rough design was made for a system with 2 coils, leaving a completely free gap of 1.5 m all around, except for bracing supports.

This completely iron-free design may not be optimum. The problem of stray field is a severe one. Providing a complete iron return (with perhaps a viewing hole in one pole tip) is likely to raise the cost to \$4 million to \$5 million, however. [Crude estimate by W. Selove, based on two separate approaches: 1) comparison with

*Private communication.

a magnet designed for the 1968 Summer Study costed by Brobeck: 4 m diameter, 40 kG, 1.25 m gap; $2.5 million; 2) comparison with the CERN Omega magnet: 3 m diameter, 18 kG, 2 m gap; $2.3 million (1967), of which $0.7 million is iron.]

If optical viewing is not required, pole tips could be inserted in the iron-free magnet. Even without a full return path this would probably increase the field to 35 - 40 kG.*

II. MEASUREMENT ACCURACY

We now take up the question of the measurement accuracy necessary and obtainable.

1. For experiments of the type $\pi^- p \rightarrow C + D$, as an example, with C a high-momentum forward particle, one may wish to trigger on a narrow-mass range for D. Examples are: a) diffraction dissociation of the target nucleon, b) baryon exchange with "backward" resonance emission. For both these processes, the uncertainty in $(\text{mass})^2$ is

$$\Delta m^2 \approx 2M_p \, dp.$$

where M_p is proton mass and dp is uncertainty in outgoing (or incoming) particle. To separate individual resonances, one would like Δm^2 to be as small as perhaps 0.2 or 0.3 $(\text{GeV})^2$--consider the ρ and A_1 for example, or the N^* (1,000), N^* (1,515), and N^* (1,688) regions. This calls for dp ~ 0.1 to 0.15 GeV/c.

2. To be sure of not missing slow π^0's, one would also like to have the energy balance good to about m_π or better. This gives the same requirement of about 0.1 GeV/c.

For the single-magnet system we are discussing, with any of the detection systems mentioned, Δp for high momentum tracks (> 10 to 20 GeV/c) will be measurement limited. In this case one has

$$\begin{bmatrix}\text{pure} \\ \text{internal} \\ \text{measurement} \\ \text{(8 optimal hits)}\end{bmatrix} \Delta p_{\text{MeV/c}} = \frac{19\, \epsilon_{\text{cm}} \left(p_{\text{MeV/c}}\right)^2}{\left(L_{\text{cm}}\right)^2 H_{\text{kG}}} \quad . \tag{1}$$

This formula applies for the case of 2 hits (digitizings) at each end of a circular arc, and 4 hits in the middle region. The error in the sagittas for this case is $\Delta s = \epsilon/\sqrt{2}$, where ϵ is the rms setting error, and $\Delta p/p = \Delta s/s$. Values of ϵ currently being obtained are ~ 0.02 cm for optical chambers and 0.03 cm for streamer and wire chambers. Using 0.02, we have

*John Stekly, private communication.

$$(\Delta p)_{\text{measurement}} \approx \frac{0.4\, p^2}{L^2 H} \begin{pmatrix} p - \text{MeV/c} \\ L - \text{cm} \\ H - \text{kG} \end{pmatrix} . \qquad (2)$$

This expression shows that Δp increases rapidly with p. For L in the range of 5 meters, and H in the range of 20 - 30 kG, $(\Delta p)_{\text{measurement}}$ reaches 100 MeV/c at $p \sim 35 - 40$ GeV/c.

Thus a field of this length and strength can give readily a Δp of 100 MeV/c for tracks up to 30 - 40 GeV/c. One would like to go much higher of course. There are two methods of doing this:

1. Measure more points. Readily possible with streamer or optical chambers. Raises upper limit of p, for constant Δp, only by the 1/4 power of the number of points. Probably permits one to go to 60 GeV/c fairly readily.

2. Add a "lever arm" to the magnet by putting additional trajectory-locating detectors (spark chambers, etc.) downstream. Osborne,[7] and Ascoli,[8] have pointed out that this technique sharply improves the Δp. For an elementary examination of this effect, we consider a high momentum trajectory which passes for a length L through a magnetic field H, and then through a field-free region for a further length L_2. (See Fig 1.) Examination shows that to a good approximation p is determined purely by measuring the angle α ($\approx 1/2\ \theta_{\text{magnetic deflection}}$), by measuring the "y" coordinate at the 3 points indicated--i.e., Δp is determined purely by the external measurement. One has

$$\frac{\Delta p}{p} = \frac{\Delta\theta}{\theta} \approx \frac{2\Delta\alpha}{\theta} . \qquad (3)$$

Neglecting internal measurements, and neglecting coulomb scattering everywhere (study shows these approximations to be reasonable), we see that measurements should be made of y_2 with the greatest precision (multiple "hits"). If we take L_2 to be 1 or 2 times L, which will turn out to be a reasonable choice, we should then measure y_1 with the next greatest precision and y_3 with the least. We take the following approximation

4 hits at y_1: error $= \epsilon/\sqrt{4}$

8 hits at y_2: error $= \epsilon/\sqrt{8}$

2 hits at y_3: error $= \epsilon/\sqrt{2}$.

Then for $L_2 = L$, we have $\Delta\alpha = 1.2\ \epsilon/L_2$, and for $L^2 = 2L$ we have $\Delta\alpha = 1.6\ \epsilon/L_2$. We average these by

$$\Delta\alpha \approx 1.4\ \epsilon/L_2 \begin{pmatrix} L2/L = 1 \text{ to } 2; \\ 14 \text{ optimal hits} \end{pmatrix}. \tag{4}$$

$$\frac{\Delta p}{p} \text{ is then given by } \frac{2\Delta\alpha}{\theta}, \approx \frac{2.8\ \epsilon/L_2}{0.3\ HL/p},$$

or

$$\begin{bmatrix} \text{pure} \\ \text{external} \\ \text{measurement} \\ \text{(14 optimal hits)} \end{bmatrix} (\Delta p)_{MeV/c} \approx \frac{9\ \epsilon_{cm}\ (p_{MeV/c})^2}{(L_2)_{cm} (L)_{cm} (H)_{kG}}. \tag{5}$$

Comparing with (1), we see that by making L_2 twice as large as L, the pure external measurement gives about 4 times the accuracy of the pure <u>internal</u> measurement. When one takes into account the additional accuracy obtained by using both external and internal measurements, one obtains this improvement factor of 4 with fewer than 14 hits.

For $\epsilon = 0.02$ cm, $L = 500$, $L_2 = 1{,}000$, and $H = 30$, (4) gives $\Delta p = 100$ MeV/c at 90 BeV/c.

Thus a 5-meter track length in 30 kG, and a following free flight path of 10 meters, allows the measurement of downstream tracks to an accuracy of ± 100 MeV/c up to about 40 - 50 BeV/c by internal measurement, and up to 90 BeV/c or so by external measurement.

It should be remarked that an accuracy considerably less good than ± 100 MeV/c would be adequate for many purposes, particularly if one has good detection capability for neutrals. Consequently, a magnet system of the dimensions and field strength discussed here would actually have considerable analysis capability for momenta far beyond 100 BeV/c.

Transverse Dimensions

Although a magnet with a 5 m circular field region may be easier to build than one with constant rectangular aperture, we remark here on the fact -- a large transverse dimension is not needed for most purposes. We discuss the relation between the available transverse dimension of the magnet and the momentum accuracy for lower momentum tracks.

Consider a track produced at an angle ϕ. (We neglect dip effects.) We take the measurement region to correspond to a transverse dimension L_T. Then (see Fig. 2) neglecting curvature of the track, we see that for the case shown $\ell = L_T/\sin\phi$. If Δp for this track is measurement limited, then from (2) we have

$$\Delta p = \frac{0.4\, p^2}{H\ell^2}, \approx \frac{0.4}{H}\left(\frac{p \sin\phi}{L_T}\right)^2 .$$

Since p sin ϕ is the transverse momentum p_T, we have

$$\Delta p \approx \frac{0.4}{H}\left(\frac{p_T}{L_T}\right)^2 . \qquad (6)$$

Thus tracks of constant p_T will have constant Δp. Very few tracks will have $p_T > 3{,}000$ MeV/c. For $p_T = 3{,}000$ MeV/c, and H = 30 kG, (6) shows that $\Delta p \approx 50$ MeV/c for $L_T = 50$ cm. When we consider the angular turning in the field, the situation worsens slightly. In the worst case, for a track emitted near 90°, the transverse momentum uncertainty could be as large as 50 MeV/c for a 3 BeV/c track. This is an unlikely large transverse momentum; nevertheless, since the accuracy, from (6), increases rapidly with L_T, it is desirable to use a slightly larger transverse dimension than ±50 cm. This is, of course, no problem if the field is make circular, as may be desirable anyway for reasons of simplicity. It is also worth noting that a large degree of openness in the sides of the magnet region is of great value in allowing flexibility of triggering, and of π^0 detection arrangements.

Angular Error

Angle errors, for the system we are considering, are satisfactorily small. By comparison with the 1968 Summer Studies, e.g., in A. 1-68-35 by Derrick and Kraemer, adjusted for the appropriate radiation length in a spark chamber or streamer chamber system as compared to hydrogen, one finds that the uncertainties in transverse momentum due to angle errors will be typically less than 5 to 10 MeV/c. As far as uncertainty in effective-mass values is concerned, the contribution of angle errors is also in reasonable balance with the contribution of momentum errors for effective-mass values in the region of several BeV.

III. ARGUMENTS FOR A SINGLE-MAGNET SYSTEM

In the light of the preceding evaluation of measurement accuracy, we now collect some of the arguments for favoring a large single-magnet system of this kind over a separated-magnet system for many purposes.

1. For a total magnet cost little larger than for several typical 2-magnet systems, one obtains a system which will provide: a) 4π detection capability; b) highly accurate Δp for tracks up to 100 BeV/c momentum; for momenta up to 50 BeV/c this high accuracy (~ 0.1 BeV/c or better) is obtained from purely internal measurements.

2. The overall length of the system is relatively short, so that downstream Cerenkov and π^o detectors can be relatively small in area and thus relatively economical.

3. As compared to a typical separated-magnet system, the tracking of particle trajectories is relatively simple; this is likely to provide substantial economies in computer time for data reduction.

4. As compared to a typical separated-magnet system, one has visual (or equivalent wire chamber) detection capability for fast strange particles, over a complete region of about 5 meters downstream from the target. This could be particularly important for the case of cascaded (i.e., successive) decays.

We merely mention briefly the basic argument in favor of building a large single-magnet system of this kind. The basic reason is to get higher sensitivity than the bubble chamber can, with comparable (or better) 4π sensitivity, both to charged particles and to π^o's, and with highly practical triggering capability for many experiments.

Event rates, for a system with, say, a 1-meter LH_2 target and a beam of 10^6 particles/pulse, can run as high as 4 events/μb/pulse, or 100,000 events/μb/day. Compare this to the 25-foot bubble chamber, which, 1) can give a maximum of a few events/μb/day, 2) is not readily used in a triggered mode, and therefore in general requires the measurement of many candidate events for each event of final interest.

Neutral Pion Detection

The importance of having large solid-angle detection capability for π^o's, both slow and fast, cannot readily be judged at this time. Two things can be said, however, to indicate why we believe such a capability is important. 1) For deep inelastic μ scattering, where present (e-p) data suggests some kind of form-factor-free effect in the proton, no one knows just what is knocked out of the proton. It may prove to be very important to be able to detect π^o's, both slow and fast, produced in this process. 2) At the beam energies at which NAL experiments will concentrate, it is known that the large majority of all hadron interactions produce multiple π^o's. In order to untangle cascade decays of excited meson and baryon states, and in order to draw any conclusions other than simply statistical ones about the nature of most 50 to 100 BeV interactions, it is likely to be very important to be able to detect all π^o's produced, at least their angles, and if possible with at least a rough measurement of the energy. For this purpose of large-solid-angle efficient π^o detection, to go along with effective detection of slow charged particles, a large vertex-region chamber is essential. All practical systems for this purpose involve at least a $(1.5\ \mathrm{m})^3$ magnetic field region around the vertex.

Finally, for good flexibility in triggering, it is highly desirable to have a very open geometry around the target. This speaks for a magnet with a large gap available in all directions in the vicinity of the median plane of the apparatus.

We should remark here on a question of comparison between this single-magnet type design and a hybrid or separated-magnet type design. We wish to point out that if one wants to detect the decay angular distribution of a forward-going quasi-stable particle state, the question of solid-angle acceptance of a downstream "spectrometer" magnet may be of critical importance. As L. Osborne[7] has shown in a separate report for some realistic examples, a system with limited forward acceptance angle, even if it accepts say 50% of all the decays of a particular resonance state, is reasonably likely to fail to pass just those parts of the angular distribution which are necessary to determine the spin of the resonance.

Detection System

The detection system to be used with this magnet could be optical spark chambers, streamer chamber, or wire chambers. Each has its enthusiasts, and each has certain advantages, although in fact the ways in which data from these various systems are currently being reduced to physics results are showing a considerable convergence. For example, the Omega Project report describes the contemplated use of human guidance, with CRT display and light pen, to assist in pattern recognition of complicated events; this is precisely the event "recovery" system now used with several bubble-chamber type measuring devices. The fact is that a multi-plane wire or optical-chamber system produces a set of digitizings very much like that produced by a flying-spot device measuring bubble-chamber or streamer-chamber tracks.

It would almost surely be useful to have the detection "guts" for this magnet prepared and mounted so as to be fairly readily replaceable or interchangeable.

For specific triggering systems which could work effectively with a magnet system of this kind, we refer to several reports being independently prepared, by L. Osborne,[6] by H. Anderson,[4] and by G. Ascoli.[9] The experiment studied last year by D. H. White,[10] and a more extensive similar experiment being examined this year by Gittelman,[5] could also be readily carried out, and triggered, using the magnet described here. For further examples of triggering arrangements we also refer to some instances treated in the CERN report on the Omega Project, NP Division, Internal Report 68-11.

We note that the question of the degree of field homogeneity required will affect the choice of optical vs non-optical detector. At NAL a higher degree of precision in momentum measurement, ~ 0.1%, will have to be available than generally used in the past. Magnetic fields can be measured to this accuracy with present technology, but the appropriate mapping of the field and the analysis of particle trajectories so as to take into account field inhomogeneities may present some practical difficulty in terms of time required. There appears to be no doubt that field measurements and trajectory analysis of requisite accuracy can be carried out--the question is what amount of measurement time and computer time are required. If the amount of time is unsatisfactorily large, a non-optical detector, with no holes in the pole pieces and thus with correspondingly more uniform field, might be favored. Whether field homogeneity is very important could probably be determined by a short study using present analysis programs. (See also Report SS-107 by Ascoli and Selove.)

IV. FINAL REMARKS

Finally, this project needs a name, and perhaps the name Alpha Project would be suitable, since the whole idea has evolved to something similar to the Omega Project. Of course this is a bargain-size Omega-type project. Note that an elementary approach would indicate that if a 3 m magnet is appropriate for CERN energies up to 20 or 25 BeV, then from Eq. (1) one might expect to need a magnet perhaps 3 or 4 times that size for NAL energies. For constant Δp (and constant H), one needs magnet size L proportional to p. However, we can in fact get away with a magnet of perhaps \$3 million cost (probably one should allow \$4 million in a rough estimate) compared to the \$2.3 million magnet of Omega Project, principally because at these higher energies one can get highly effective additional measurement accuracy by following the high-energy trajectories downstream 5 or 10 meters past the magnet, as Osborne and Ascoli pointed out. This added external measurement is practical for high-energy outgoing particles because their angles are so concentracted forward. The net effect is that a 5-meter magnet plus a 10-meter free flight space has roughly the same Δp precision one would get if one used a continuous magnetic field for 10 meters following the interaction and then made <u>no</u> further external measurements. Thus by making this magnet with an HL^2 product about 2 to 3 times that of the Omega magnet, one can measure, for fixed Δp, momenta up to 2 to 3 times that for the Omega magnet, using purely internal measurements; using external measurements in addition, one can go to momenta about 5 times that for the Omega magnet. This seems about the right momentum range to aim at for this first such project at NAL.

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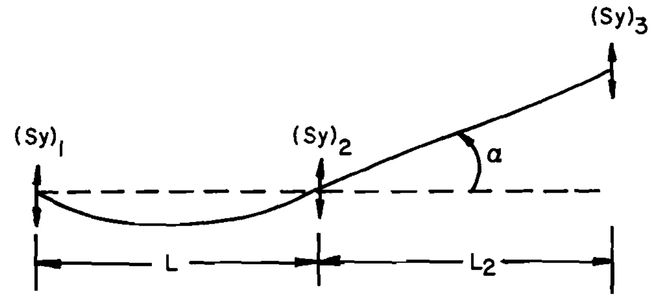

Fig. 1. Use of additional straight portion of track ("lever arm" to improve the momentum accuracy of a curvature measurement.

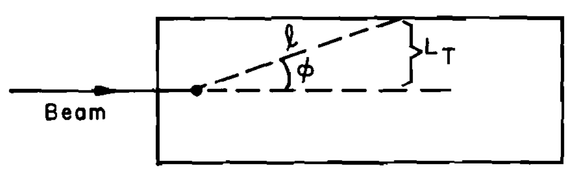

Fig. 2. Determination of transverse dimension requirement for magnet.