THE FUTURE PROGRAM OF CHARM PHYSICS WITH THE EHS APPLICATIONS OF HOLEBC AND THE RCBC

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1. INTRODUCTION

I started preparing this paper with a view to examining specifically the possibilities of developing the RCBC for charm physics. It quickly became clear however that it is timely to review the whole of the EHS high resolution program and to discuss the evolution of the spectrometer without prejudice to the vertex arrangement. This I will briefly attempt to do. The physics possibilities are extremely exciting and we will see that both HOLEBC and a suitably developed RCBC system have different regions of application in which they excel. A prime objective of this paper is to define the regions of technical development that, in my opinion, should be pursued in the next year and to indicate the physics return that might follow in the future.

It should be remembered that the essential components of the EHS, including the RCBC, were designed for physics in 1973/4. The design was based on an overall optimisation of the set up to give as complete an analysis as possible of hadronic interactions over the full kinematic range i.e. $-1 \lesssim x_F \lesssim +1$, for incident momenta up to ∿ 400 GeV/c. The matching between RCBC, M1 and the downstream spectrometer is based on general kinematic conditions and error analyses and has not therefore changed. In 1974 SLAC and FERMILAB discovered the ψ/J and "charm" was born experimentally. In 1975 we realised that it should be possible to detect and study the charmed hadrons using a high resolution bubble chamber, and this has been demonstrated using LEBC in NA13 and NA16 (1979, 1980). We must now consider the possibility of developing the RCBC (and if necessary other components of the spectrometer), or changing the vertex arrangement, to allow the direct study of charmed particle production and decay. I will try to answer the following questions in this talk:

i) Since we have shown with NA16 that we can detect charmed particle decay vertices using the high resolution hydrogen chambers LEBC and now of course HOLEBC, why is it interesting to consider the RCBC?

ii) If we are to consider RCBC for high resolution physics, what resolution do we need to achieve to be useful and what kind of experimental program can be foreseen.

To answer these questions it is first necessary to look briefly at the physics we will be trying to do and what information is needed to provide useful data.

2. PHYSICS WITH CHARM AND BEAUTY AT THE EHS

The physics that we are in principle able to study can be stated briefly as follows:

(a) Particle lifetime measurements for which we need length measurement plus reconstructed momenta on an unambiguously identified sample of events.

(b) Mass determinations for some (rare!) states. Clearly absolute mass determinations can only be made for events with identified unambiguous decay modes and having precise and absolute momentum measurements.

(c) Particle decay modes. With the exception of the simple decay modes of the D-mesons little is known and much has to be done in this area. In particular the study of Cabibbo favoured versus non-favoured decays for all ground state particles plus the measurement of leptonic and semi-leptonic branching ratios is crucial to the theoretical understanding of the decay mechanisms and is correlated to the questions of lifetime differences.

Experimentally we know from SPEAR that the decay modes are in general complex, involving strange particle plus pions, with a mean multiplicity of ∿4 for the charmed mesons. Charmed baryons will of course have the additional problem of having a baryon, which could be strange, in the final state. The importance of particle identification cannot be overstated particularly when low branching ratio Cabibbo unfavoured decays have to be established unambiguously.

The fact that the EHS is a very complete spectrometer providing both precisely measured momenta and particle identification puts us in a unique situation for the detailed study of charm decay physics in the future.

It should be noted that the above topics require a reasonable sample of unambiguously identified decays. There is no dependence on production mechanisms and to a first approximation, problems arising from the spectrometer acceptance can be corrected by simple weighting procedures depending only on phase space calculations in the decay process.

(d) Production mechanisms in proton induced reactions.

Two fundamental questions have to be answered and again the EHS is probably uniquely suited to do so.

i) To understand the mechanism and S-dependence of the cross section for the production of the Λ_c^+ particle. The ISR data indicates large cross sections (300 - 1500 μb) depending on the assumed rapidity distribution. The data favours a flat y-distribution suggesting a high cross section with a significant diffractive contribution. At SPS energies, where $\sqrt{S}$ is down by only a factor 2.5, the only evidence for Λ_c^+ production comes from NA11 (75 ± 50 μb!). It is very important that we find the Λ_c^+ signal directly to study both the decay and the production mechanism in p-p.

ii) To understand the beam-dump data. The beam dump is a complex indirect method of detecting charmed particle production in p-Cu, Fe interactions. Cross section estimates have varied from 100 - 200 μb for inclusive D production in 1978-79 to ∿10 - 30 μb for the same process in 1980-81. Differences come partly from statistics but more importantly from changes in the interpretation - linear A dependence or $A^{2/3}$, x_F distribution at production ..... etc. Direct measurement of the production x_F distributions in hydrogen for each particle i.e. D, F, Λ_c, plus their leptonic or semi leptonic branching ratios, is crucial to the interpretation of this data. The EHS can provide this information. It is then possible to ask if the total beam dump signal can be explained by charm production and decay or if some new process or particle must be invoked.

(e) Production mechanisms in pion or kaon induced reactions.

It is important to compare meson induced reactions with proton induced because of the presence of a valence antiquark in the pion (or kaon) and hence the possibility to have charm production via a quark annihilation mechanism. A comparison between the x_F distribution and cross section for charm production in π-p, K-p, p-p and $\bar{p}$-p can help to understand the relative contributions from the quark annihilation ($q\bar{q}$), quark-gluon, (qg) and gluon gluon (gg) mechanisms. The particular interest in kaon induced processes obviously follows from the fact that the antiquark (or quark) in the Kaon is strange and hence can be followed to the final state. Moreover we expect high cross sections for the production of F-mesons which are particularly interesting in their decay properties.

(f) Photoproduction of charm.

Photoproduction is obviously exciting because it has the possibility of a relatively high charmed particle yield from a "simple" hadronic final state trigger. It is well suited to the study of charm decay properties and possibly to the threshold production and detection of beauty. This is the motivation of the Photoproduction Letter of Intent I140.

3. CONDITIONS TO BE MET BY THE SPECTROMETER

From the above considerations it is clear that the physics program is both extensive and exciting provided that the spectrometer can give the relevant data. The following conditions must be met experimentally:

(a) Good high resolution vertex detection. This is the essential feature that distinguishes our technique and spectrometer from all others and is an enormous advantage. At its lowest level direct vertex detection provides a clean highly efficient off line trigger on charm. If the spectrometer is subsequently considered only as a "counter set up" with a hydrogen target this alone provides a background rejection factor of a thousand to one - admittedly at some considerable cost in effective data rate! Vertex detection however does considerably more than that. The correct assocation of outgoing tracks to their vertex of origin reduces, indeed in the case of zero topological ambiguity removes, the combinatorial problem amongst charged particles in the final state (given particle identification - see later).

Since we are in general dealing with highly complex events; a pair of charmed decays with a mean additional charged particle multiplicity of 10 or 12, the above considerations are paramount. In addition however direct vertex detection provides a measurement of the decay length which is essential for lifetime determination.

The need for high resolution is clear, we will discuss how high and the implications for RCBC in the next section, however for the physics described above it is not yet enough! High resolution is a necessary condition but is not in itself sufficient to study the charm and beauty physics of interest.

(b) Charged particle momentum and angle measurements.

Clearly, for any purpose of reconstruction, precise measurements of charged particle momenta are required. The original design of the EHS was optimised to minimise the error on effective mass calculations between pairs of particles emerging from interactions in the RCBC. This defines the field in M1 and the position and resolution required in the spectrometer planes, and also the specification of the second lever arm, beginning with M2. The whole is optimised to give resolution typically in the range 10 - 20 MeV at the mass of a D-meson i.e. $\simeq 2$ GeV/c^2 over the whole momentum range to 400 GeV/c^2. NA16 has shown that the performance in practice is in agreement with the design specification (see Alan Poppleton's talk). Typical charged particle momentum errors are $\sim 1\%$ and angle errors at the vertex are $\sim 0.1 - 0.2$ mrads.

In considering the charm questions the important differences that arise between an RCBC experiment and, for example HOLEBC upstream of M1 in the NA26 arrangement, come from the acceptance variations. The RCBC situation is optimal in that momenta and angles are well determined from the lowest momenta (few MeV/c) seen in the bubble chamber (by range) to the maximum momentum of the SPS. Since the detection efficiency for the charm decays in the chamber does not depend strongly on the momentum of the charmed particle it is important, if we wish to reconstruct charm produced at all x_F and with a variety of beams, that the decay products are well measured over as large momentum range as possible. For NA16 for example the acceptance was only good for D mesons produced in 360 GeV interactions with x_F positive and this is in general true for any arrangement like NA26 (or NA16'), having HOLEBC upstream of M1 in a "field free" position.

(c) Particle identification.

The identification of charged particles from charm decays is crucial to any future charm experiment. The EHS system in principle spans the full momentum range using ionisation in the bubble chamber (RCBC), SAD, ISIS, FC and TRD. The full spectrometer should be operational in 1982 and its performance in this respect should make it unique amongst fixed target spectrometers. The importance for charm studies has already been evaluated in the previous section.

(d) Neutral particle detection.

Most charm decay modes involve final state π^o, η^o mesons. The IGD and FGD are designed to maximise the acceptance for gammas from π^o's produced at +ve x_F. NA16 has demonstrated the value of π^o detection for charm reconstruction. Precision on the $\gamma\gamma$ effective mass is typically 15 MeV/c^2 (FWHM) and on the reconstructed π^o momentum $\sim$few%.

For the future the neutral particle detection will be completed by the addition of the FNC and INC - the neutral hadron calorimeters. These again will be of great value for charm physics because of the importance of K^o_L and sometimes $n,\bar{n}$ in the decays. Again acceptance is optimised for a production vertex at the centre of M1.

4. THE DETECTION OF CHARMED PARTICLE DECAY VERTICES: WHAT RESOLUTION IS NEEDED?

The method and resolution needed to detect decay vertices was studied, at first using Monte Carlo generated events, by Robert Sekulin, Dave Crennell and myself. Subsequent experience with NA13 and NA16 has shown that the ideas are substantially correct and the problem well understood. Two levels of detection can be identified:

i) To show that an interesting decay has occurred in an event and therefore that the event can be selected as containing charm or some other short lived decay and;

ii) To clearly see the decay vertex and hence correctly associate all the the charged particles with their vertex of origin.

Clearly ii) requires better resolution than i). The parameters that determine the visibility of a decay are illustrated in Figure 1; they are the decay length L, the transverse decay length x and the maximum impact parameter y_{max} of charged secondaries from the decay.

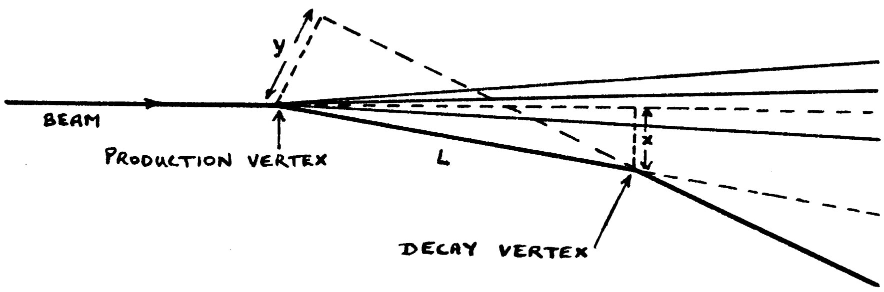


FIG 1.

In the absence of other charged particles in the event it is only the decay length L that determines the visibility of the decay and it is only necessary that the resolution be significantly better than L. This is the situation near threshold; for example in the SLAC photoproduction experiment (see the proposal RL BCG Physics Note 122, C Fisher 1979). At high energies the presence of many additional charged particles from the production vertex (typically 10 - 12 at 300 GeV!) seriously confuses the problem and the resolution required is considerably higher than at low energies. We discuss this situation now:

To show that a decay has occurred in the event we must find one track or more that does not point back to the primary vertex i.e. having a significant impact parameter <y> compared with the experimental resolution. We have:

$$y = L\sin\theta_{decay}$$

We can write

$$y = \frac{p_\perp}{(p^*_{11}/\beta + E^*)} \cdot \tau c$$

where $p_\perp$, p^*_{11} and E^* refer to the decay product in the rest system of the charmed particle,

τc is the actual lifetime multiplied by c and β is the velocity of the charmed particle in the lab in units of c. In the approximation $\beta \simeq 1$ we have $y_{max} = f_{max}\tau c$ where f depends only on the decay kinematics. The value of f is estimated using a Monte Carlo assuming a phase space distribution for the decay products in the D decay for any given mode. We use the best available (SPEAR) data on the decay modes and average over all decay modes to find the probability that y_{max} in a decay exceeds some value, say twice the experimental resolution, and hence that the event is detected. The result of this Monte Carlo analysis, is shown in Figure 2.

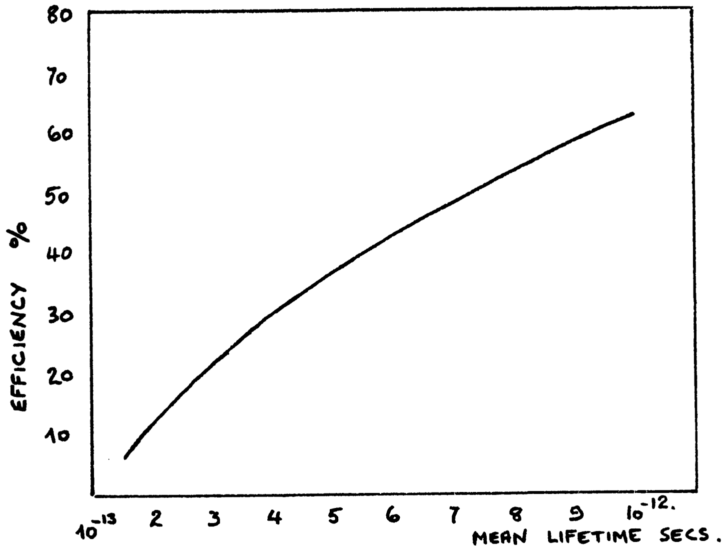


Fig. 2 Monte Carlo estimate of the efficiency to detect D-meson decays by requirement that $y_{max} > 100$ µm - NA13 result

An important feature of this analysis is clearly that the detection efficiency, i.e. the the values of y in the decay, depends only very weakly (through β) on the momentum of the charmed particle, i.e. essentially does not depend on the beam momentum or the x_F at production. We are therefore well placed to study production mechanisms.

It is also a simple matter given the Monte Carlo detection efficiency for a given lifetime or resolution to derive the detection efficiency, using the impact parameter technique, for any other lifetime or resolution.

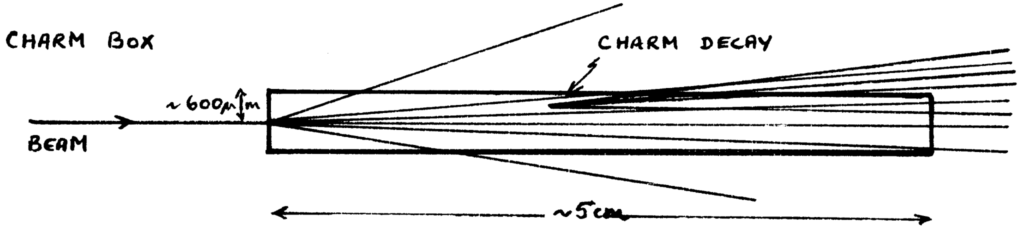
Consider now the question of the clear detection of the decay vertex i.e. a visible vertex separated from other final state particles in the event. The important parameter is now x the transverse decay length

$$x = L\sin\theta_{prodn} = \frac{p_\alpha}{m}\,\tau c \cdot \frac{p_\perp}{p_D}$$

$$x = \frac{p_\perp}{mc} \cdot \tau c$$

Thus x depends only on the transverse momentum at production and the lifetime. Note again that x is a transverse decay length and therefore does not depend on the beam momentum or the x_F production. Two consequences follow from this simple expression:

i) That for charmed particle decays we expect $\tau \lesssim 2.10^{-12}$ secs and $p_\perp \lesssim mc$ so that $x \lesssim 600\ \mu m$. Thus all decay vertices are expected to be within 600 μm of the forward direction independant of the momentum of the D, and hence the decay length L (which can easily be several centimetres). Thus we have the idea of a charm box containing all decay vertices.



ii) In general we expect $p_\perp < mc$; typically $\frac{p_\perp}{mc} \sim {}^1/5$. The probability that the decay vertex is clearly resolved can only be estimated by Monte Carlo, this time depending on the production distribution of the additional particles in the event.

In Table 1 we give the results of the decay impact parameter Monte Carlo analysis for various interesting lifetimes and resolutions.

Table 1

Detection Efficiency % from Impact Parameter Technique

Resolution / lifetime	5 μm	20 μm	40 - 50 μm
10^{-12}secs	94%	82%	64%
3.10^{-13}secs	84%	50%	20%
1.10^{-13}secs	59%	12.5%	1%
5.10^{-14}secs	35%	1.5%	-

The efficiency for clear vertex detection is of course considerably less and depends on the production mechanism and associated complexity of the event. As a rule of thumb! divide by two or three! The third column represents approximately the condition for NA16, the second (20 μm) the expected performance for HOLEBC (NA16') and the third (5 μm) the ultimate (?) expected from holographic HOLEBC.

The following conclusions can be drawn:

(a) Any future charm experiment must have a detector with resolution better that NA16 - however for charm studies in general we are sensitive to and can usefully study charm production and decay using a detector with resolution 30 - 40 μm. This would be a realistic aim for a large chamber such as RCBC which has the considerable analysis advantages discussed above.

(b) Classical HOLEBC (NA16') should give us excellent data on charm decay properties and production in the forward direction. Clear vertex detection should be considerably better than in NA16.

(c) Holographic HOLEBC must be seriously pursued. It offers the only real possibility of reaching lifetimes of interest for Beauty (with the possible exception of threshold production where the cross section is likely to be too small to access). The other advantages of holography - in particular the increase in depth of field and hence cross section sensitivity is also critical to such future experiments which clearly require very high sensitivity and a selective charm trigger.

5. CONCLUSIONS

The conclusions I wish to emphasise are the following:

(a) The physics of charm requires not only high resolution but also good acceptance for the decay products of charm particles by the spectrometer.

(b) The EHS is very well matched to the problem because of the complete nature of the analysis of individual events that is possible.

(c) The acceptance properties however are matched by design to the RCBC i.e. having the production vertex at the centre of M1. RCBC also, because of its volume and conventional views. provides an essential component of the spectrometer for low energy tracks which would normally be outside of the acceptance. This will include particles from charm decays and in many cases associated particles from D^* decays etc.

RCBC with a resolution ~ 20 μm would be ideal. RCBC with a resolution $\lesssim 40$ μm would be an excellent chamber for charm studies and could combine the charm physics with a general soft physics program.

(d) HOLEBC is of course also excellent for direct charm detection: two developments are recommended!:

- i) To consider the possibility of putting HOLEBC inside M1 to improve acceptance - alternatively to significantly increase the M1 gap keeping HOLEBC in its NA26 position. This would allow much improved charm studies however it might be necessary to augment HOLEBC with additional detectors inside M1 (streamer chamber).
- ii) To fully develop holography with HOLEBC. This is essential for a future charm program based on prompt triggering. The study of Beauty production and decay will clearly depend critically on having a holographic HOLEBC coupled with a suitable trigger. Note that such an experiment may also need modifications to the EHS to cope with rate limitations and possibly also to improve acceptance.

Thus high on the list of technical developments, at the vertex region, for our future charm physics program I would put:

(a) Holography with HOLEBC.

(b) High resolution optics (classical and (or holographic) for RCBC (running at 30 - 40 μm).

(c) Triggering on charm (not discussed here but see the talk of Sven Olaf Holmgren).

(d) Possible modifications of M1 - increase the gap(?). Streamer chamber(?) etc.

Many other considerations are relevant, for example obviously the acceptance question becomes more severe as the beam momentum is reduced if the vertex is not situated in M1. Quantitative estimates of these effects are in progress or will be done via Monte Carlo studies, for future experiments. High on the list of desirable features is of course the detection of strange particle decays occurring close to the production vertex as well as downstream in the spectrometer.

It is important in 1982 that both the technical questions and limitations referred to above be explored and that suitable Monte Carlo studies are completed to evaluate quantitatively the advantages and disadvantages of the various options.