HIGH RESOLUTION BUBBLE CHAMBERS AND THE OBSERVATION
OF SHORT-LIVED PARTICLES

L. Montanet and S. Reucroft
CERN, Geneva, Switzerland

1. INTRODUCTION

The idea of using a high resolution small bubble chamber to observe charm particles was first proposed by Colin Fisher [1] in 1977. The proposal was guided by the experience gained with the track sensitive targets used inside large bubble chambers such as BEBC and the ANL 12', making possible the construction of a so-called "clean" bubble chamber, that is, one with no spurious boiling. The optical extrapolation from classical bubble chamber techniques is two fold. On one hand, high spatial resolution may only be achieved by photographing small bubbles (say 50 μm diameter) with a sufficiently high density (say 60 bubbles/cm). On the other hand, the optics have to be adjusted to preserve this resolution. In classical optics, this is achieved at the expense of a reduction of the depth of field.

These developments led to the construction of LEBC [2] (an acronym for LEXan Bubble Chamber) which was used in 1979, at CERN, in a test experiment. This first step is reviewed in sect. 2.

Of course, a bare bubble chamber (no magnetic field, no spectrometer, no particle identification, etc.) cannot, by itself, provide enough information to identify charm particles and to measure their lifetimes.

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and gamma detection. For this purpose, the European Hybrid Spectrometer (EHS) [3] was used with LEBC in an experiment performed at CERN in 1980. In parallel, a small heavy liquid bubble chamber, BIBC (Bern Infinitesimal Bubble Chamber) was used in conjunction with a large streamer chamber and associated spectrometer, also at the CERN SPS. This second step is reviewed in sect. 3.

The resolution achieved with LEBC in a classical optics configuration was of the order of 40 μm . One can show that this is enough for charm particles produced in hadron interactions at SPS energies so long as their lifetime is greater than $\sim 5 \times 10^{-13}$ s. It was commonly assumed, in 1978, that charm particles had a lifetime of $\sim 7 \times 10^{-13}$ s, the dominant decay being assumed to be a Cabibbo favoured transition. Meanwhile, we have learned that charm particles may not all have the same lifetime, other decay diagrams, such as quark annihilation ones, being possibly important. Experimental results using emulsion techniques with ν and γ beams [4] indicate that most charm particles have lifetimes of the order of 10^{-13} s. Under these conditions, resolutions of the order of 5 to 10 μm are necessary. This can be achieved with holography so long as sufficiently large densities of the correspondingly smaller bubbles can be produced to define the path of the short-lived particles. The idea of using holography with bubble chambers is not new [5] but the advent of short-lived particles with lifetimes in the range 10^{-14} to 10^{-12} s has brought considerable interest to this technique. In June 1980, M. Dykes et al [6] have demonstrated the feasibility of the technique, using BIBC and a simple in-line Fraunhofer hologram arrangement. The application of holography to high resolution bubble chamber experiments is reviewed in sect. 4 and sect. 5.

Holography not only gives access to better spatial resolution, it also introduces the possibility of dealing with larger beam intensities, hence achieving higher sensitivities. These fascinating potential improvements over the classical bubble chamber technique open the door to a vast experimental field which we attempt to review in sect. 6. This review, of course, cannot be exhaustive.

2. DIRECT OBSERVATION OF CHARM PARTICLES WITH LEBC

In 1979 a first experiment was performed at CERN to observe directly charm particles in a bubble chamber specially designed and built for that purpose, LEBC, a cylindrical chamber of 20 cm diameter with a depth of 4 cm.

The choice of hydrogen as a chamber liquid was justified, not only because of the interest of studying charm production off a single nucleon, but also for reasons of background reduction, in particular when the selection of charm candidates is based only on topological information as was the case in this first experiment.

The track sensitivity was achieved by expanding the 1.1 litre volume using a thin membrane forming the rear flat end of the cylinder. A hydraulically driven piston acted on this membrane. The stroke was ~ 1 mm. The front end of the cylinder was made of a 25 mm thick Lexan optics window glued on the chamber cylinder. To reduce the number of spurious interactions, 15×100 mm² beam and exit windows of 2 mm thickness were machined into the 25 mm thick cylindrical chamber wall (fig. 1).

The chamber body was made of Lexan, a thermoplastic polycarbonate which conserves good mechanical properties at low temperatures. All metal-Lexan connections (heat exchanger, filling valve, pressure transducer, vapour pressure bulb) were sealed without gluing by a hot-cold shrinkage technique.

The length and amplitude of the pressure cycles could be adjusted by a servo-loop. Cycle lengths as short as 5 ms were achieved and the chamber was operated at a frequency of 30 Hz.

Bright field illumination was obtained with a light source of 30 J, 30 μ s flash duration, reflected by Scotchlite glued on the expansion membrane. A flash delay of 300 μ s was used to photograph bubbles of ~ 40 μ m diameter. At a hydrogen temperature of 29.1 K (the static pressure being of 7.4 bar, and the pressure drop ~ 4.1 bar) the observed bubble density was ~ 80 bubbles cm. In the first experiment described

here, one camera was used. In the subsequent experiment described in the next section, two cameras were introduced to allow for 16° stereoscopic reconstruction of the interactions.

In the first experiment, a lens of 240 mm focal length with F/16 aperture was used and the demagnification was $m = 2.14$. In the second experiment, $F = 180$ mm, F/11, and $m = 3.25$.

In the classical theory of diffraction [7], the spatial resolution is given by

$$r = \frac{m_1}{\pi} \frac{\lambda D}{2a} = 1.22 \lambda \frac{F(m+1)}{2a}$$

where m_1 is the position of the first minimum of $2J_1(m)/m$, $J_1(m)$ being the Bessel function of first order

λ = wave length of the light (0.52 μm)
 D = distance object lens = $F(m+1)$
 F = focal length
 m = demagnification
 $2a$ = aperture of the lens.

This gives $r \sim 30 \mu\text{m}$ for both experiments. Indeed, the bubble diameters were measured using a micro-densitometer to be $42 \pm 6 \mu\text{m}$ in space, not far from the diffraction limit. Another practical lower limit to the desired bubble diameter is imposed by film measuring devices. These operate most efficiently when the image of a bubble on film exceeds a certain size. With $M = 3.25$ we reach this limit (12 to 15 μm) [8].

With such a high resolution, the depth of field is limited to a few millimeters

$$\Delta \sim 3 \frac{r^2}{\lambda},$$

with $r \sim 30 \mu\text{m}$ $\Delta \sim 5.4$ mm.

The optics of the SPS H2 beam was such that it could be easily contained within these 5 mm of depth; its cross section in the chamber being $2 \times 80 \text{ mm}^2$.

An interaction trigger was used to select events occurring within a sensitive gate of $\sim 1 \text{ ms}$ around the pressure minimum and to start the timing of the bubble growth. The trigger consisted of five scintillators, the smallest being $2 \times 100 \text{ mm}^2$ to define the profile of the useful beam. Because of interactions outside the fiducial volume, (in the walls of the bubble chamber, for example) $\sim 50\%$ of the pictures gave a correctly timed event in hydrogen. To eliminate most of the beam tracks out of time which create an undesirable background of large bubbles in the pictures, a kicker magnet was introduced for the second experiment [9]. it displaces the primary proton beam off the target until the bubble chamber reaches its optimal sensitivity conditions, and displaces the beam again $\sim 50 \text{ } \mu\text{s}$ after the useful interaction has been detected by the trigger. The effect of the kicker can be judged in fig. 2, where two "events" are shown, one from each experiment (without and with the kicker).

A total of 110 000 pictures containing 48 000 interactions in the fiducial volume, and corresponding to a sensitivity of 2.5 events per microbarn, were taken in a $340 \text{ GeV } \pi^-$ beam at the CERN-SPS. We summarize now the results of this experiment [10].

The background to charm candidates due to secondary interactions in hydrogen or due to gamma conversions can be quantitatively evaluated and is negligible. The main source of background is due to strange particle decays, which can be confused with charm decays for the most likely topologies and cannot be removed by effective mass evaluation in the absence of momentum measurements. To remove this background, one must rely on the fact that charm and strange particles have very different lifetimes. The selection of the candidates makes use of two geometrical quantities, labelled x and y in fig. 3

$$x = \frac{p_{t_1}}{p_1} L = \frac{p_{t_1}}{m_1} \tau c.$$

where p_{t_1} = transverse momentum of the decaying particle
 p_1 = momentum of this particle
 L = decay length
 τ = lifetime
 m_1 = mass.

In hadronic interactions and for a large range of incident momenta (above threshold), the approximation $p_t \lesssim m$ is known to work quite well. Therefore, x can be approximated in the following way

$$x \lesssim \tau c,$$

i.e. x only depends on τ in this first order approximation. For strange particles ($\tau \sim 10^{-10}$ s) one expects that most decays will occur within a road centred on the direction of the incident particle, ± 3 cm wide. For charm particles ($\tau < 10^{-12}$ s) this width is reduced to ± 300 μ m. By selecting the candidates within a road ± 600 μ m wide, one keeps essentially all charm decays but eliminates a large fraction of the strange particles. However, the scanning for charm decays is not based only on the detection of a decay vertex and on the evaluation of x , which is often difficult to estimate near the production vertex, but also on y , which measures the distance by which a charged particle coming from a secondary vertex would miss the production vertex, indicating in this way that some secondary activity has occurred. It remains then to decide if this secondary activity is due to a secondary interaction. These are recognisable in hydrogen by the simple rule that secondary interactions due to a charged particle lead to an even number of prongs, (odd for neutral ones) whereas charged decays lead to an odd number of prongs (even for neutral ones). The distance y is related to the transverse momentum of the decay product with respect to the charm particle line-of-flight

$$y = L \frac{p_{t_2}}{p_2} = \tau c \frac{p_1}{m_1} \cdot \frac{m_2}{p_2}$$

where p_{t_2} = transverse momentum of the decay product with respect to the decaying particle line-of-flight

p_2 = momentum of the decay product

m_2 = mass of the decay product.

To first order, y is independent of the momentum

$$y \sim \tau c,$$

and the lower limit of y which can be reached by human observation at the scanning table sets the lower limit of the lifetime with which decaying particles can be detected. Monte-Carlo studies taking into account various decay modes of the charm particles have been performed [11] to estimate the scanning efficiency as a function of lifetime, assuming that all events with $y > 3 r$ (i.e., $y > 100 \mu\text{m}$) are detected. One can check by double and triple scans that this assumption is correct. Fig. 4 shows that with this cut one reaches efficiencies of $\sim 50\%$ for $\tau \sim 7 \times 10^{-13}$ s. By precise measurements of the bubble chamber tracks, one could in principle increase this efficiency to $\sim 50\%$ for $\tau \sim 1 \times 10^{-13}$ s: the r.m.s. deviation of the measurements from a straight line being of the order of $6 \mu\text{m}$ in space for LEBC. However, this method would require the systematic measurement of all the events, an unthinkable procedure for the time being in view of the limited measuring capacity of our laboratories. Human scanning remains the only practical solution for the detection of charm candidates.

Fig. 4 shows an approximate linear dependence of the detection efficiency on particle lifetime. Therefore, if the production mechanisms lead to a mixture of charm particles with equal production weights, the detection efficiency depends only on the average mean lifetimes of these charm particles. This would be the case if D^+D^- , $D^+\bar{D}^0$, $D^-\bar{D}^0$ and $D^0\bar{D}^0$ are the main production modes with these four associated production channels having the same cross section, but the $D^\pm$ and D^0 having different lifetimes.

Going back to the first experiment done with LEBC, charm candidates have been searched for in a box defined by $x < \pm 600 \mu\text{m}$ and $L < 3 \text{ cm}$. The best signals are to be found in the events having a pair of decay candidates or single 3-prong decays, these topologies being obviously less

sensitive to the strange particle background. The background is evaluated by using the quantitative observations of single and double decays outside the "charm box". The results are that 20 pairs are observed in the box whereas the expected strange particle background is 8.2. This excess of 12 pairs is still present if the limit in x is raised to $\pm 1000 \mu\text{m}$ or if L is reduced to 2 cm. A similar excess is observed (14 pairs, 4 expected) if a cut on y is introduced ($y < 1000 \mu\text{m}$), supporting the interpretation that this excess is due to charm decays. Eight 3-prong decays are observed inside the cut $x < \pm 600 \mu\text{m}$, whereas a background of 2 events can be evaluated (due to $K^\pm \rightarrow \pi^\pm \pi^+ \pi^-$ and $\Sigma^+ \rightarrow p e^+ e^- \gamma$ decays, and 4-prong secondary interactions with an undetected prong). The excess of single 3-prong events is compatible with the excess of pairs, using the known branching ratios for charm particles and assuming an equal production of $D^+ D^-$, $\bar{D}^0 D^-$, $D^0 D^+$, $D^0 \bar{D}^0$.

The most natural and simple interpretation of these results is in terms of charm production. In fact, making the assumptions discussed above one finds that if interpreted as direct charm particle observation, then the excess of pairs gives a total $D\bar{D}$ cross section of $\sim 40 \mu\text{b}$; the excess of 3-prong decays gives an inclusive D cross section of $\sim 35 \mu\text{b}$ [10].

It is clear, however, that any detailed analysis of the production and decay properties would need an improvement of the technique in three areas:

- (a) momentum analysis, particle identification and gamma detection, in order to remove completely the strange particle background and to obtain dynamical information on the production and decay of the charm particles;
- (b) better spatial resolution to reduce biases against the shortest lived charm particles;
- (c) better statistics.

In the next section, we shall report on the attempts made to solve the first series of problems. We shall then see how holography may be the solution for the second and perhaps the third category of necessary improvements.

3. DIRECT OBSERVATION AND IDENTIFICATION OF CHARM PARTICLES

To solve the problems encountered in the identification of the signal observed in a bare bubble chamber like LEBC, it was proposed to equip LEBC with a downstream spectrometer for momentum analysis of the charged particles from the production and decay vertices of the charm particles. At SPS energies and for hadronic production, one expects charge multiplicities of the order ~ 10 and the momentum resolution should be of the order $\sim 1\%$ to identify unambiguously charm particles and separate them from the abundant strange particle production. The double arm EHS spectrometer [3] has been built precisely for this purpose and thus it was that LEBC was coupled with EHS for the NA16 experiment [12]. Equipped with six large drift chambers of four planes each, these planes being orientated according to the "butterfly" geometry [13] in order to minimize the multitrack ambiguities, this spectrometer reveals itself as a powerful instrument for complex event reconstructions. In the actual case of NA16, the EHS spectrometer was slightly reshuffled to optimize the acceptance (Monte-Carlo simulations have shown that $\sim 50\%$ of the D decays could be completely momentum analysed). Since LEBC could not operate in a magnetic field, the large vertex magnet foreseen for the normal operation of the EHS spectrometer was replaced by a 0.5 Tm magnet, downstream of LEBC. This magnet gives momentum analysis of the charged particles which do not reach the second lever arm of EHS and is followed by a six plane multiwire proportional chamber, W2. To boost the performance of W2, a high precision high resolution inclined wire chamber V1 [14] was inserted between the magnet and W2. Fig. 4 shows the experimental layout. An insight into the performance of this spectrometer, coupled to the bubble chamber information, is shown in fig. 5 where a sample of 2-prong neutral decays has been plotted according to the reconstructed effective mass

($\pi^+\pi^-$, $p\pi^-$, $\pi^+\bar{p}$ or e^+e^- hypotheses): clear peaks are observed at the expected masses for K_S^0 (498.0 ± 1.0 MeV/c²) and Λ^0 ($\bar{\Lambda}^0$) (1116.5 ± 1.5 MeV/c²). The full widths at half maximum of these distributions (10 MeV/c² and 8 MeV/c², respectively) are in good agreement with those expected from the EHS design momentum precision of $\Delta p/p \sim 1\%$.

EHS also provides gamma detection and reconstruction [3] for nearly all π^0 's produced in the forward hemisphere, including, in particular, those coming from charm decays. The energy resolution is 1 to 3% for fully reconstructed π^0 's in the energy range 1 to 100 GeV. It is of course impossible to decide, a priori, the origin of any reconstructed π^0 , between production and decay vertices of charm candidates. Kinematical constraints are however greatly improved by π^0 information and this can lead to unique identification of charm particles for those with one or two π^0 decay modes.

Some of the charged particle identification features foreseen for the final version of EHS [3] were available during the data taking stage of NA16. Ultimately, EHS will include a set of Cerenkov detectors, transition radiation detectors and a large volume ionization drift chamber (ISIS) for identification of charged particles in the 3 to 200 GeV momentum range. At the time data were taken for NA16, a prototype version of ISIS was available. The detector surface was 4×2 m², covering the full acceptance of the spectrometer, and the ionization sampling was obtained with up to 80 independent sense wires. This gives π identification between 3.5 and 30 GeV/c and electron identification up to 9 GeV/c. ISIS also provides useful track information which helps to solve pattern recognition problems.

A photograph of an NA16 charm event is seen in fig. 6(a) with a sketch in fig. 6(b). The event is a 360 GeV/c π^-p interaction giving eight charged particles and two neutral ones which materialize as 2-prong decay and 4-prong decay, respectively. All six decay tracks and three tracks from the production vertex are successfully reconstructed. In addition six photon showers are identified in the γ detection system and these can

be associated to give three unique π^0 signals. With the interpretation of the particles as shown in fig. 6(b) the 2-prong decay of $D^0 \rightarrow K^- \pi^+ \pi^0 \pi^0$ gives a D^0 mass of $1857 \pm 22 \text{ MeV}/c^2$ and the 4-prong decay of $\bar{D}^0 \rightarrow K^+ \pi^+ \pi^- \pi^-$ gives a D^0 mass of $1862 \pm 9 \text{ MeV}/c^2$. No other assignment of particles gives any recognisable strange or charm particle mass. The ionisation data from ISIS is consistent with all mass assignments. The D^0 and $\bar{D}^0$ lifetimes are $(2.1 \pm 0.1) \times 10^{-13} \text{ s}$ and $(5.9 \pm 0.1) \times 10^{-13} \text{ s}$, respectively. More details of the analysis of this event are given elsewhere [15].

This event gives an example of the possibilities one has with a high resolution bubble chamber, a precision spectrometer such as EHS and charged particle identification and γ detection. Other NA16 charm candidates are presently being studied. The present analysis situation indicates that the experiment should give 50-100 fully reconstructed charm particle decays.

At the same time that NA16 was taking data with LEBC and EHS, another collaboration [16] was collecting data with the small heavy liquid bubble chamber BIBC [17]. The film from this experiment has been fully scanned yielding several hundred measurable candidates for charm decays. These events are presently being analysed and are expected to give a few identified charm particle decays.

The combination of a high resolution vertex detector with a downstream spectrometer, gamma detectors and charged particle identification is therefore possible and offers a solution to the first set of experimental problems encountered with a bare bubble chamber. From the experimental point of view, we have not yet exhausted the possibilities offered by a bubble chamber, such as LEBC, photographed by classical high resolution optics and coupled with an apparatus as sophisticated as EHS. Indeed, it is interesting to consider extra statistics in an NA16-type hadronic experiment with a chamber such as HOLEBC equipped with the kink-detector described in sect. 5, or alternatively expose HOLEBC to the high energy photon beam mentioned in sect. 6 and study the photoproduction of charm. Both these ideas are attractive, but would be limited in resolution by the practical limit of classical optics of about $20 \mu\text{m}$ resolved bubble

diameter. We now see how the use of holography could improve the experimental situation with respect to the spatial resolution needed for the detection of short lived particles and with respect to the sensitivity of the vertex bubble chamber detector needed for the study of rare processes.

4. THE APPLICATION OF HOLOGRAPHY TO BUBBLE CHAMBERS

One may find several reviews on the application of holography relevant to our discussion. We shall refer to B.J. Thompson [18] for basic concepts and definitions.

A hologram is the record of the interference pattern formed between a reference optical field and the optical field of interest. When the hologram is illuminated with a beam of light equivalent to the reference field, the original field of interest is recreated. Both the amplitude and phase of the field of interest are stored and re-created, whereas in classical optics, only the square of the amplitude is recorded. In practice, the field of reference will be a laser beam, and the field of interest will be the light of this original beam which has been diffracted by the bubbles in the bubble chamber. Since the bubble chamber is mainly transparent, the hologram can consist of the interference pattern between the light diffracted by the bubbles and the undiffracted light of the same incident beam, but this is not a necessary condition and one can imagine a set up where the reference beam would, at least partially, avoid crossing the bubble chamber.

The resolution achieved with holography is given by the same formula as before

$$r = 1.22 \frac{\lambda D}{2a}$$

$2a$ being now the useful width of the hologram film. For example, with $\lambda = 700 \text{ nm}$, $D = 12 \text{ cm}$ and $2a = 100 \text{ mm}$, a resolution of $\sim 1 \text{ }\mu\text{m}$ can in principle be achieved.

The depth of field is of the order of the coherence length of the laser. it can reach several tens of centimeters, independant of the achieved resolution.

A sketch of the simplest optical arrangement, utilising in-line Fraunhofer holography, is given in fig. 7.

Some preliminary optical bench tests [19] encouraged M. Dykes et al [6] to perform a feasibility test, recording for the first time bubble chamber tracks on a hologram. This test also explored, under real experimental conditions, practical limitations such as resolution, depth of field, bubble density, track density, etc.

For this feasibility test, the small bubble chamber BIBC [17] was used. This chamber is well suited for holography tests, with its two optical windows which allow through-illumination and in-line Fraunhofer geometry. It is a heavy liquid bubble chamber designed to produce high bubble density tracks, another useful characteristic if track elements made of very small bubbles must be recognised. The experimental layout is shown in fig. 8.

The tests were made using a ruby laser which delivered single light pulses of 10 mJ in 10 ns, the wave length being 694 nm. The light pulse was synchronised with the particle beam and with the bubble chamber expansion. The fast beam ejection system gave $\sim 2.4 \mu\text{s}$ bunches of particles every SPS cycle ($\sim 12 \text{ s}$). This fast ejection guaranteed that all the tracks photographed on a given hologram had similar bubble size. Holograms were made on glass plates and on film, both coated with Agfa-Gevaert 10 E75 emulsion. Two different positions were tried during the tests, the film being at 10 and 18 cm from the particle beam axis. Tracks of different bubble sizes were recorded by varying the time interval between the passage of the beam and the laser light pulse. The number of beam tracks per photograph was varied between 10 and 150, the beam being spread over the full cross section of the bubble chamber ($\sim 60 \times 35 \text{ mm}^2$).

The information recorded on these holograms allowed the reconstruction of 6 μm diameter bubbles with high contrast and high quality throughout the full depth and along the full transversal dimension of the bubble chamber (fig. 9). The reconstruction of 10 μm wires mounted in front and behind the bubble chamber windows demonstrated that the optical quality does not deteriorate over a depth of field as large as 9 cm, much more than needed for the small fast cycling bubble chambers which could be operated with holographic optics. That it is possible to make use of this large depth of field is demonstrated by the observation of tracks lying in the same optical plane and separated by less than 3 mm in depth. One can therefore accept more tracks per expansion in a holographic bubble chamber than in a conventional bubble chamber; at the scanning and measuring stage, it suffices to focus on the track of interest, the other beam tracks remaining invisible or creating a background which remains quite acceptable even with up to 250 incident beam tracks.

Of course, with the simple in-line geometry adopted here, excessive liquid turbulence deteriorates the quality of the picture. Practical limits will have to be investigated for every specific case.

Another important characteristic of picture quality is related to the bubble density; as the bubble size decreases, this density must increase to allow the scanner to recognise track elements. Scaling down current bubble chamber parameters (150 μm diameter, 13 bubbles/cm, or, for LEBC, 40 μm diameters, 80 bubbles/cm), we would need densities of ~ 400 bubbles/cm for bubble diameters of $\sim 5 \mu\text{m}$. With heavy liquids such as freon and propane, bubble densities of 400 b/cm are easily achieved. In the tests described above, densities up to 1000 b/cm have been observed. It may be more difficult to achieve large bubble densities with liquid hydrogen since it will require operating conditions close to the foam limit. Tests are in progress at CERN to investigate such points and, in fact, minimum ionizing tracks with primitive bubble density of ~ 200 bubbles/cm have already been observed in a test run with HOLEBC at the PS [20].

Although the tests made with BIBC had the great virtue of demonstrating the feasibility of the use of holography for bubble chambers, a certain number of points were left open. We have already mentioned some of them. Others involve the choice of the film for recording the holograms, the influence on the resolution of the film to object distance and the choice of a laser.

P. Lecoq and P. Olivier [21] have shown that, for resolutions of the order of a few μm or more, no serious deterioration of the resolution is observed when the holograms are made with 0.17 mm polyester film base as compared to ordinary glass plates. However, problems could arise if resolutions of the order of 1 μm were sought, as would be the case for the study of particles with life times $< 10^{-15}$ s.

As indicated above, the resolution depends linearly upon the distance D between object and film, everything else remaining the same. With $\lambda = 550$ nm and hologram diameters of 60 mm, this linear dependence is empirically found to be of the form

$$r(\mu\text{m}) \sim 0.1 D(\text{cm}) + 5(\mu\text{m}).$$

For a small heavy liquid bubble chamber, D can be as small as ~ 10 cm, giving $r \sim 6$ μm . For a hydrogen bubble chamber, however, it is difficult to bring the film this close to the beam axis and the geometry probably cannot be as simple as represented in fig. 7. Various solutions can be considered; one of them would be to introduce a relay lens which would image the bubble chamber at a convenient position for hologram recording.

In a physics experiment with a fast cycling bubble chamber, a ruby laser such as the one used in the tests made with BIBC, would not be satisfactory because of its limited pulse repetition rate. In general, flash lamp pumped lasers cannot be triggered fast enough. On the other hand, excimer - pumped dye lasers can be randomly triggered over ranges of 0.1 to 30 Hz and offer an intrinsic pulse duration of 15-20 ns, these

characteristics making them highly suited for the operation with fast cycling bubble chambers. Moreover, the choice of dye enables the dye laser output to be tuned from the near ultra-violet to the near infrared [22].

Most of the remaining questions relating to the practicability of holographic bubble chamber photography will be answered by two test experiments planned for operation at the CERN SPS before 1982 and discussed in the next section.

5. PROTOTYPE EXPERIMENTS WITH HOLOGRAPHIC BUBBLE CHAMBERS

To take advantage of the gain of resolution offered by these holographic bubble chamber techniques together with the essential information provided by the EHS spectrometer, an experiment has been proposed [23] to study charm particle production and decay using a holographic high resolution hydrogen chamber (HOLEBC) and the European Hybrid Spectrometer. The experimental lay out, similar to the NA16 set up of fig. 4, is shown in fig. 10. LEBC is now replaced by HOLEBC, which is installed at 1.8 m upstream of the large aperture spectrometer magnet M1. The EHS spectrometer will provide momentum analysis of 80% of the charged particles with a resolution of $\sim 1\%$. A high precision high resolution proportional inclined chamber (PIC1) will be introduced in M1 to help track following and hooking between the bubble chamber and the spectrometer. Particle identification will be provided by the aerogel Cerenkov SAD, the pictorial drift chamber ISIS a forward Cerenkov and transition radiation detectors. This set of detectors cover a momentum range of particle identification from 3 to 200 GeV/c [3].

As for NA16, the on-line trigger of the bubble chamber laser and camera will be a simple interaction trigger, with no attempt at selecting on-line charm candidates. In these conditions, one expects that only 0.1% of the holograms may contain charm decays, and the data accumulation rate will be limited by the camera cycling time. The aim of this prototype experiment is not so much to accumulate large statistics on charm decays (it is difficult, at the present stage of the art, to scan a very large

number of holograms) but to gain experience and prepare future experiments with large sensitivities, using tighter triggers and higher beam intensities. A step in this direction will be taken with the help of a high precision drift chamber [24] which could detect charm decays missing the production vertex by a quantity y larger than the minimum detectable distance given by the drift chambers. As seen above (sect. 2), this minimum distance must be of the order of $100\text{ }\mu\text{m}$ to be useful. It is proposed to use this information off-line, in a first step, to select the holograms to be scanned.

HOLEBC is equipped with two optical windows to facilitate in-line holography. The expansion membrane is therefore at the bottom of the chamber (fig. 11) and the heat exchanger at the top. Beam windows are cut into the Lexan chamber body to fit the beam profile. The useful chamber volume is 12 cm along the beam, $5 \times 7\text{ cm}^2$ cross section. The design cycling rate of 50 Hz has already been achieved in a test run.

One of the main uncertainties of this proposed experiment is how to achieve and maintain the very high bubble densities required to make good track elements with $5\text{--}10\text{ }\mu\text{m}$ bubbles; the liquid hydrogen has to be expanded as close as possible to its foam formation limit. Any parasitic boiling must be avoided, justifying the use of Lexan for the construction of HOLEBC since it is the best way to build a "clean" bubble chamber. As discussed before, this difficulty is much less severe with heavy liquids. This is one of the reasons why another prototype experiment is planned to use a small fast cycling heavy liquid bubble chamber [25]. In fact, the tests with BIBC make it seem highly probable that such a device can be used successfully with holography. This experiment will therefore take an additional step forward by using an on-line trigger to fire the laser and select interactions which have a larger probability to contain charm decays than the average ones. Since semi-leptonic decays are relatively important for charm particles, this trigger will make use of a muon detector. The experimental lay out of the proposed experiment [26] is shown in fig. 12. In principle, the muon filter enriches the fraction of holograms containing charm by a factor ~ 10 , thus allowing the accumulation of ~ 1000 charm events with $\sim 5 \times 10^4$ holograms. The data acquisition rate can be

optimized with 150 incident particles over a beam spill of 30 μ s, using a 25 Hz bubble chamber, HOBC [25], filled with C_3F_8 over a fiducial length of 10 cm (fig. 13). Within a few days of data acquisition, this experiment could accumulate enough statistics to compare the charm production cross sections for $\pi^\pm$, $K^\pm$ and $p^\pm$ beams at 100, 200 and 300 GeV/c with a precision of $\sim 10\%$.

A natural extension of this experiment could be a search for beauty with a sensitivity of 1 evt/nb. Triggering then on 2 muons and assuming that ~ 500 beam tracks can be sent through HOBC per expansion, $\sim 3 \times 10^8$ interactions could be sampled, the number of holograms being of the order of 10^5 .

Unfortunately, a muon filter is not easily compatible with good downstream information for momentum analysis, gamma detection and particle identification.

We have mentioned two proposals [23,26] which have already been approved by the CERN SPSC and denoted the numbers NA26 and NA25, respectively. One of them tries to obtain the maximum possible information from a set of downstream detectors, but makes no on-line attempt to enrich the sample of useful holograms. The other one sacrifices the downstream information but uses the on-line selection offered by a muon filter. Ideally we would like to take data with the complete downstream information but restrict the hologram acquisition to those containing interesting events. Whereas no ideal solution has yet been suggested for this problem one possible compromise experiment is reviewed in the next section. Also in the next section we note other possible experiments which may take advantage of the holography technique as applied to small bubble chambers.

6. FUTURE STEPS: TOWARDS HIGH RESOLUTION AND HIGH SENSITIVITY

In order to directly observe, with good detection efficiency, particles with lifetimes down to $\sim 10^{-14}$ s one needs to photograph bubbles of diameter 5-10 μ m. Technical limitations have prevented

classical optical systems from reaching this resolution; however, the use of holography appears to solve the problem. Sufficiently high bubble densities to clearly define track segments are easily attained with heavy liquid bubble chambers and should also be possible with hydrogen bubble chambers.

As outlined in the previous section, however, there still remains an outstanding problem before one can hope for high sensitivity experiments [27]. This is the problem of selecting events on-line in a reasonable way such as to reduce the amount of hologram scanning; the problem of triggering.

One elegant way around this problem, at least for charm physics, may be approached in a photoproduction experiment [28] using HOLEBC, EHS and the H₂ tagged bremsstrahlung photon beam [29]. The beam of a few $\times 10^7$ photons (with energy > 1 MeV) over the 2s SPS flat top would provide a high energy ($75 \text{ GeV} < E_\gamma < 100 \text{ GeV}$, say) hadronic photoproduction event every ~ 1 -2 flat-tops. A sensitivity of ~ 1 evt/nb should be achievable in a 20 day run. It would be possible to trigger the laser-camera system on these hadronic photoproduction events using the photon beam tagging system and a conventional interaction trigger. The trigger would select all hadronic final states and should therefore give minimum bias; the fraction of holograms containing charm should now be ~ 1 -2%, a factor of at least 10 better than with hadronic production. The holograms would contain, in addition to the hadronic event, many background tracks in the form of Compton electrons and photon conversion pairs; with conventional optics these would cause problems but with holography techniques should be mainly out of focus and therefore should not affect the picture quality.

With a sensitivity in excess of 1 evt/nb and with a resolution of 5 μm or better, a search for beauty events would be feasible. In addition the τ -lepton should be accessible via the F-decay [30].

A potential limitation to the experiment would be posed by the relatively low intensity of charged particles that can be tolerated by EHS; in particular ISIS, which constitutes $\sim 6\%$ of a radiation length, cannot easily handle high fluxes. This limitation can only be evaluated in practice in an actual test run of the experiment; a proposal for this is in preparation [28].

An alternative way to take full advantage of the increase in sensitivities offered by the holographic technique, is to use neutral hadron beams. This does not solve the trigger problem but would prevent charge particle flux limitations from reducing the attainable sensitivity. One possibility could be a neutral K_L^0 beam, with $\sim 10^5 K_L^0$ per spill in the 80-200 GeV/c momentum range [31]. It may also be possible to investigate nucleon-antinucleon annihilations, using an antineutron beam obtained from a $\bar{p}$ beam by charge exchange. This possibility would become very exciting if a 400 GeV/c $\bar{p}$ beam is extracted from the SPS.

The idea has been investigated [32] of running a heavy liquid holographic bubble chamber in a 300 GeV hyperon beam, the advantage being that it could give access to the direct observation of charmed hyperons like the S_0 and A_0 (composed of dsc quarks) with a Σ^- beam and the T_0 (ssc) with a Ξ^- beam. At 300 GeV/c, the cross section for production of A_0 could be as large as 10 μb and the hyperon beam could contain $\sim 20\%$ of Σ^- . A run of ~ 20 days would provide 80 000 holograms with $\sim 400 S_0$ and A_0 directly observed.

One may complete this list of suggestions with a much more classical proposal involving a direct measurement of the π^0 lifetime. One could observe directly the line of flight of a π^0 produced by charge-exchange, starting with a 300 GeV/c π^- beam. The mean path of a 150 GeV/c π^0 would be $\sim 50 \mu\text{m}$, and an accurate lifetime could be determined, using the decay $\pi^0 \rightarrow e^+ e^- \gamma$ to determine the π^0 decay point.

With the possibility of using high intensity beams with holographic bubble chambers, the problem of the duty cycle of these detectors becomes more acute than in the past. At 30 Hz, and with available sensitive gate

widths smaller than 800 μ s, the duty cycle of the present bubble chambers is less than 3%. Even at ultrasonic frequencies it can probably not be better than 10%. To make better use of the beams, we need high resolution continuously sensitive bubble chambers. The idea of using the neck of a Venturi tube for the sensitive volume of the chamber is not new [33], but has had no practical application for bubble chambers with classical optics. With the advent of the holography techniques, which needs limited size bubbles, the idea can be resurrected [34]. The basic idea is to renew continuously the sensitive volume of liquid around a converging-diverging nozzle (fig. 14). Since the bubbles would move in a turbulent flow at a mean speed of 50 m/s, a flash delay as small as possible is required. In fact, in C_3F_8 , for example, a flash delay of 1 μ s is necessary to photograph bubbles of 5 μ m diameter and this would be acceptable. For the same reason, the flash duration must be short; we have seen that laser illumination corresponds to flash durations of ~ 10 ns, and this would also be acceptable.

A prototype version of this continuously sensitive bubble chamber is presently being tested at CERN and shown in fig. 14.

Several years ago the trend in bubble chamber physics was towards bigger and bigger devices intended as general facilities. Most laboratories were abandoning the development of bubble chamber technology. With the exception of a few apparent cranks, bubble chamber physicists were reeducating themselves in counter techniques. It was commonly said that, as a useful tool in high energy physics, the bubble chamber was dead. The advent of the small "disposable" bubble chamber and the use of esoteric high resolution optical techniques has given the bubble chamber a new lease on life. It now appears to be the best device for the study of short lifetime particles produced with small cross sections and the future is indeed an exciting one.

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FIGURE CAPTIONS

- Fig. 1   Section sketch of the high resolution hydrogen bubble chamber LEBC as used in experiment NA16.
- Fig. 2   (a) A photograph of an event from NA13;
- (b) A photograph of an event from NA16. The absence of tracks with large bubbles in fig. 2(b) shows the improvement obtained with the beam kicker magnet.
- Fig. 3   Definition of the quantities x and y described in the text.
- Fig. 4   The general layout of the prototype EHS including LEBC as used for experiment NA16.
- Fig. 5   (a) $\pi\pi$ effective mass distribution for a sample of V^0 decays identified as K^0 decays.
- (b) $p\pi^-$ and $\bar{p}\pi^+$ (hatched) effective mass distributions for a sample of Λ and $\bar{\Lambda}$ decays. Analysis of such events is used to evaluate the behaviour of the spectrometer and analysis programs and to give a measurement of the mass resolution.
- Fig. 6   The first fully reconstructed charm event from NA16:
- (a) A photograph of the event;
- (b) A sketch of the event based on measuring machine digitizations. The momenta of all reconstructed tracks are given. The mass hypotheses are based on kinematic information but are, in every case, consistent with the measurements of the pictorial drift chamber ISIS. Note that the scale of fig. 6(b) is expanded laterally to clarify the event.
- Fig. 7   Sketch of a set-up for the use of in-line holography to record bubble chamber tracks.

FIGURE CAPTIONS (Cont'd)

- Fig. 8 Sketch of the set-up used to holographically record the bubble chamber tracks in the test with the bubble chamber BIBC.
- Fig. 9 A photograph of an event from the BIBC test using in-line holography. Resolved bubbles are typically 6-8 μm in diameter and tracks have several hundred bubbles/cm.
- Fig. 10 General layout of the EHS including the holographic hydrogen bubble chamber HOLEBC as proposed for experiment NA26.
- Fig. 11 Section sketch of HOLEBC.
- Fig. 12 General layout for the proposal of experiment NA25 including the holographic heavy liquid bubble chamber HOBC and a muon detector based on the GARGAMELLE EMI.
- Fig. 13 Photograph of the body of HOBC.
- Fig. 14 A photograph of a prototype version of the continuously sensitive bubble chamber COBC.

FIG. 1

FIG. 2a

FIG. 2b

FIG. 3

FIG. 4

FIG. 5

FIG. 6a

FIG. 6b

FIG. 7

FIG. 8

FIG . 9

FIG.10

FIG. 11

FIG. 13

FIG.14