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A RAPID CYCLING HYDROGEN BUBBLE CHAMBER WITH HIGH SPATIAL
RESOLUTION TO VISUALIZE CHARM DECAYS

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1. INTRODUCTION

In the Autumn of 1979, mass values and decay modes for D mesons were already established from leptonic production with e^+ , e^- colliding beams. Emulsion exposures in neutrino beams indicated lifetimes between 10^{-12} s and 10^{-13} s, and neutrino beam dump experiments yielded indirect evidence for hadronic charm production with estimated cross sections from 10 μb to 50 μb . In striking contrast to leptonic charm production, hadronic interactions should produce associated charmed pairs and visual observation with a bubble chamber seemed to be the only clean method of separating these double decays from the strange particle background. In this talk we report on the construction and operation of such a bubble chamber, named LEBC, which stands for LEXAN bubble chamber.

2. DESIGN CRITERIA

The expected event topology from a D meson of rest mass m_0 , produced at an angle θ with momentum p (transverse momentum p_T), and decaying after a lifetime τ with the decay length

$$L = p\tau/m_0 = p_T\tau/(m_0\sin\theta) \quad (1)$$

is shown in fig. 1. Assuming $p_T = m_0c = 1.86$ GeV/c and 10^{-13} s $\leq \tau \leq 10^{-12}$ s we obtain from relation (1) the transverse

distance of the decay vertex from the beam direction:

$30 \mu\text{m} \leq L \sin\theta \leq 300 \mu\text{m}$. Therefore, resolved bubble diameters smaller than $\sim 50 \mu\text{m}$ are required to detect charm decays with reasonable efficiency within the complex interaction patterns. Consequently, we need an optical system with a resolution R better than $50 \mu\text{m}$. Since R is linked with the depth of field D via the Rayleigh criterion ($R = 1.22 \sqrt{D \cdot \lambda}$, $\lambda = 550 \text{ nm}$), we expect the following focal depths transverse to the beam:

Resolution (μm)	50	40	30	20
Depth of field (mm)	12.2	7.8	4.4	2

Fig. 1 Transverse separation $L \sin\theta$ of the decay vertex from beam direction, which dictates the spatial resolution required to detect charm decays

Let us assume that our optical resolution yields an observable cross section of $5 \mu\text{b}$, so that we detect one charmed pair in 4000 beam interactions. At this rate, background events become important and therefore we chose hydrogen as chamber liquid, where the absence of neutrons allows for unambiguous discrimination between charged D decays (odd prongs) and interactions (even prongs), and the relatively large interaction - and conversion lengths of hydrogen keep the vertex region clear from secondary events.

To find around 100 charmed pairs during a 10-day beam exposure of the bubble chamber, requires about five photographed beam interactions per second (at 15% accelerator duty cycle and 60% overall data taking efficiency). To achieve this, we need 20 cm of beam length in hydrogen, 15 beam tracks per picture, 30 Hz expansion - and 15 Hz camera rate. In addition, the need for small bubbles implies high bubble density and hence deep pressure swings during the expansion cycles. To avoid the parasitic boiling, which in normal chambers is an inevitable consequence of such an operating regime, we had to build a "clean" bubble chamber, without the conventional seals around the piston and the optics window.

3. CHAMBER BODY

To meet the above design criteria, we constructed a cylindrical chamber body, with 20 cm inner diameter and 4 cm free depth (fig. 2). Track sensitivity is achieved by expanding the 1.1 l volume via a 5 mm thick membrane, which forms the rear flat end of the horizontal cylinder and is supported across its outer surface by a hydraulically driven piston. Scotchlite is glued onto the inner surface of this membrane and particle tracks are photographed in bright field illumination through a 25 mm thick window, which is glued as the front plate, on the chamber cylinder.

In order to realize a "clean" chamber, all parts of the body were constructed from LEXAN. This thermoplastic polycarbonate has a low elastic modulus and is not brittle at cryogenic temperatures. To reduce the amount of gluing, the chamber cylinder with its 2 mm thick beam windows and the expansion membrane were machined from one single LEXAN bloc. This basic structure was then vacuum sealed with the LEXAN optics window by solvent cementing the two parts along a 30 mm wide annular margin. To avoid light absorption in the optics window, we did not use normal LEXAN with its blueish tint, but ordered a special make^(*), produced with stringent precautions against dirt contamination. Then, at another firm^(**), four 1/4" thick sheets of SL3000 were amalgamated by a process, patented as

(*) SL3000 from General Electric Comp. Mount Vernon, Indiana (USA).

(**) Westlake Plastics Comp. LENNI, Pennsylvania (USA).

"press-polishing", to the final 1" thickness required. All metal-LEXAN connections required for the heat exchanger, filling valve, pressure transducer and vapour pressure bulb were sealed without any gluing by a shrinking technique: the metal parts were cooled to liquid nitrogen temperature and fitted into appropriately dimensioned borings in the LEXAN structure, which was warmed up to 45 C.

Fig. 2 Cross sections of the LEBC-chamber body (dimensions in mm)

4. EXPANSION SYSTEM

The pressure cycles are provided by a hydraulically driven piston. Its action is transmitted via the expansion membrane into the chamber volume. The membrane is fixed on its outer circular edge. Its active surface, which provides the volume change and hence determines the piston stroke, is only that section, which, due to the hydrogen pressure, rests on the piston. Therefore, this active surface depends on the piston position, the hydrogen pressure, and on the mechanical properties of the membrane.

During the beam exposures, the chamber represents a closed thermodynamic system and the static hydrogen pressure is determined by the piston rest-position between the pressure cycles. Variations of the static pressure, due to fluctuations of the hydrogen temperature, are automatically compensated by corresponding adjustments of the piston rest-position. This is possible, since the expansion motor is a forced electro-hydraulic servo-system. Its basic servo-loop compares the actual position of the piston with an input signal from a function generator, which sets the shape of the desired expansion cycle. In this way we obtained cycle-lengths as short as 5 ms. During all LEBC-exposures, the expansion system never stopped the data taking. In particular, we benefitted from its enormous flexibility when adjusting the cycle length, amplitude and rate to achieve optimum conditions.

5. CRYOGENICS

LEBC was cooled by forced circulation of two-phase hydrogen, supplied from standard CERN dewars. Liquid hydrogen is continuously transferred from the pressurized storage dewar into a 20 l container (fig. 3). Then it flows through the heat exchanger which controls the chamber temperature and finally passes through a series of heat exchangers which intercept the radiative and conductive heat loads. The inlet valve for the chamber heat exchanger maintains an adequate mass flow and its outlet valve controls automatically the pressure and hence the temperature of the two-phase refrigerant. Satisfactory operating conditions at 29.1 K hydrogen temperature were achieved with the heat exchanger set at 28.6 K at a mass flow of $7 \cdot 10^{-2} \text{ gs}^{-1}$ provided by the dewar pressurized at 7.5 bar. The static heat load of the chamber was 5 W, the dynamic one was around 0.1 W. The cool down took around 24 h, followed by 1 h filling time. Complete thermal stability was reached about 12 h after filling was completed. In spite of the unfavourable surface to volume ratio of LEBC, we achieved an excellent thermal stability of $\pm 0.01 \text{ K}$ over more than 24 h.

Fig. 3 Vertical section of the LEBC-vacuum tank with cold valves and hydrogen container at the upper part and chamber body with optics and expansion at the lower part

6. OPTICS AND CAMERAS

A point-like light source of 30 J energy and 30 μ s flash duration was installed between the vertically arranged two camera lenses (fig. 3). Its light was guided via two semitransparent mirrors into the liquid hydrogen, as if originating from the two lens apertures. From the Scotchlite, on the inner membrane surface, it was retrodirected into the two lenses, which were of the commercially available Componon-S type^(*). With 180 mm focal length and F/11 aperture we obtained 30 μ m theoretical resolution and 3.25 demagnification.

The two cameras were modified versions of the Rapid Cycling Bubble Chamber (RCBC) cameras presently built for EHS. The retrodirected flash-light is focussed by the lens onto the 50 mm wide unperforated film^(**) mounted on an hexagonal capstan of 56 mm face-lengths. Film flatness is achieved by a vacuum suck-down at the exposed and its two adjacent faces, whilst unsticking of the film is provided by venting the three other faces to atmosphere. The film is transported by rotating the capstan through 60° in order to expose its next face to the lens at a maximum rate of 20 s⁻¹.

7. BEAM EXPOSURES AND RESULTS

LEBC construction was approved by the CERN Research Board on 16 November 1978 and 6 months later first tracks were photographed in this chamber. In June 1979, a production run, known as experiment NA13, was started in a 340 GeV negative pion beam, which resulted in 110 000 one-view pictures. NA13 was performed by exposing LEBC without any downstream particle spectrometer. Therefore, in a second experiment (NA16), LEBC was placed at the vertex position of EHS, which provided momentum analysis, particle identification and gamma detection for secondaries emerging from the hydrogen interactions. For this exposure, LEBC was equipped with two cameras to permit stereoscopic event reconstruction. A typical picture is shown in fig. 4. In April 1980, 674 000 pictures were taken in a 340 GeV negative pion beam, focused to give an image of 80 mm height and 2 mm depth

(*) J. Schneider, Optische Werke, D-6550 Bad Kreuznach (Germany).

(**) 3M921.

in the chamber. This was followed in June 1980 by a 360 GeV proton exposure, which resulted in 710 400 pictures. Including all test runs, LEBC has taken a total of 1.635 million pictures in both experiments and has been cycled for more than 20 million times. The main operating parameters for the NA16 exposure are listed in table 1.

Bubble diameters on NA16 pictures of LEBC were determined by observations with a microscope (between 37 μm and 45 μm in space) and by scanning across the photographed bubbles with a micro-densitometer: $(42 \pm 6)\mu\text{m}$ in space. The rather large error margins indicate, that the tracks contain bubbles of different size. This is due to the coalescence of bubbles formed at distances smaller than their diameter at the instant of picture taking. The probability of bubble coalescence depends on the bubble density, which was determined from counting $\sim 15\,000$ bubbles in different film rolls: $(80.5 \pm 0.7)\text{cm}^{-1}$. No evidence could be found for a dependence of the bubble density either on the track location in the chamber or on the expansion number within the 67 cycles of a beam spill. From the Poisson-distribution of primary bubbles we derived the probabilities for single bubbles and coalesced ones formed within a distance of the average bubble diameter (40 μm). In this way we find, that an observed bubble density (80.5 cm^{-1}) corresponds to a density at the instant of bubble formation of 97 cm^{-1} .

The basic limit on the measurement accuracy of a particle track is its r.m.s. deviation from a straight line. This deviation, the track residual, represents a typical figure of merit for a bubble chamber. From 32 000 measured beam tracks, 18 cm long each, we found 6.2 μm r.m.s. residual in space or 2 μm on film. This value includes errors of the ERASME measuring machine at CERN, which are of the same magnitude. Larger chambers have typical track residuals of 50 μm (2 m chamber) and 250 μm (BEBC).

TABLE 1

LEBC Operating Parameters

Hydrogen temperature	29.1 K
Hydrogen (equilibrium) vapour pressure	7.10 bar
Hydrogen static pressure	8.15 bar
Hydrogen pressure minimum	4.1 bar
Hydrogen temperature fluctuations	0.01 K
Piston stroke	1.25 mm
Length of expansion cycle	5 ms
Chamber cycling rate	33 s ⁻¹
Camera cycling rate (max.)	17 s ⁻¹
SPS flat top	1.8 s
SPS cycle every	12 s
Beam gate at pressure minimum	800 μ s
Lens focal length	180 mm
Demagnification	3.25
Aperture	F/11
Depth of field	5 mm
Flash delay	300 μ s

Fig. 4 A 360 GeV pp interaction in LEBC with a neutral and probably a 1-prong charged decay. The resolved bubble size is 40 μ m