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LIQUID HYDROGEN AND DEUTERIUM DIFFERENTIAL CERENKOV COUNTERS*

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A liquid hydrogen differential Cerenkov counter was developed to detect 0.3 GeV/c ($\beta = 0.92$) pions for comparing π^+ and π^- lifetimes in a check of CPT invariance. This type of counter, previously reported, has now been improved considerably so that it gives no empty-counter counts, remains clean with no window fogging, and has a very stable index of refraction. Liquid deuterium has also been used successfully as the Cerenkov medium, and a large counter (7-inch diameter) has been made. Both the large and small (4-inch diameter) counters have cleanly separated pions and muons of the same momentum, with a peak-to-valley ratio of about $10^4:1$ for particles traversing the counter.

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I. INTRODUCTION

It is difficult to obtain an index of refraction $n \approx 1.1$, as is sometimes necessary for a focusing Cerenkov counter. A gas above its critical point may be used,¹ but very stable operation is hard to achieve. Liquid hydrogen or liquid deuterium, which have indices in this range, have the strong advantage of minimal multiple scattering of the radiating particles.

The Lawrence Radiation Laboratory 184-inch cyclotron produces a maximum flux of pions with $\beta \sim 0.9$, and hence a high-statistics pion experiment required a Cerenkov counter with $n \approx 1.1$. The experiment was a check on CPT invariance by comparing the π^+ and π^- lifetimes (Fig. 1). In the first version of this experiment² one 4-inch diameter liquid hydrogen Cerenkov counter (Fig. 2) was used to determine the number of pions of either sign which survived as a function of distance. A description of the construction and operation of this counter was given³ at the previous instrumentation conference at SLAC. A second experiment⁴ has just been completed to much higher precision utilizing two Cerenkov counters of somewhat different design and employing both liquid hydrogen and liquid deuterium. These counters, which are of 4-inch and 7-inch diameters, were designed to avoid problems found with the first counter: some empty-counter counts, window fogging, and stability of the index of refraction. In the second experiment we had more opportunity than in the first to explore counter characteristics, and some of this information will be presented below.

II. OPTICAL DESIGN

The basic optical design has been described previously,^{1,3} and hence will be discussed only briefly here. Cerenkov light generated in the liquid hydrogen or deuterium either strikes a 45 deg mirror directly or after an angle-preserving reflection from the cylindrical mirror which forms the radial limit to the Cerenkov medium. The Cerenkov light which has been reflected through 90 deg is

then focussed by a quartz lens doublet¹ to a ring aperture, the radius of which depends on the angle of emission of the Cerenkov light. It should be stressed once more that refractive optics have the advantage over reflective ones that their dispersion partially cancels that of the Cerenkov medium. Light from particles anywhere within the confines of the cylindrical mirror will be brought to this ring focus by the lenses, provided that the particles have the correct velocity and are traveling parallel to the axis of the cylinder, which is also the optical axis of the lens system. A conical light funnel beyond the ring aperture brings the light to a photomultiplier.

The difference between the optics of the older counter (Fig. 2) and the newer ones (Fig. 3) lies in the shape of the Cerenkov medium, the order of the window and mirror having been interchanged. The first counter used a sapphire window at the end of the cylindrical mirror and before the 45 deg mirror so as to provide a length of Cerenkov medium which did not vary with position across the counter. It had, however, the disadvantage that the sapphire window gave counts with the flask empty which were 0.6% of the number with the counter full. Sapphire was used because its high index of refraction should have prevented its own Cerenkov light from emerging from anywhere but the window edges, but the spurious counts resulted either from surface imperfections, which allowed Cerenkov light to escape, or possibly from weak scintillation.

In the newer counters Cerenkov light does not have to pass through a window to reach the 45 deg mirror.⁵ This mirror is immersed in the Cerenkov medium and the separation of medium from vacuum is provided by a side window⁶ which is then out of the beam. Because of the 45 deg mirror, the light-producing paths of the particles depend on the position across the counter (in one dimension), and this could produce a position-dependent efficiency. Such an effect would have had

serious consequences in our experiment and hence was investigated thoroughly; no such effect was found to better than 0.1% accuracy. This also indicates that the counter was better than 99.9% efficient for particles of the proper β and direction passing all the way through the counter. The empty-counter efficiency was found to be less than 0.01% of the full-counter efficiency.

In both the older and newer counters light was collected also from an annular region outside of the ring focus for correct-velocity particles. This light from off-axis or off-velocity particles was carried by lucite light pipes to two anticoincidence photomultipliers. In the larger counter replacement of these plastic light pipes by reflective ones resulted in an increase in pulse height.

III. CRYOGENIC FEATURES

Problems posed by using liquid hydrogen or deuterium include keeping the index of refraction constant, avoiding bubbles and turbulence in the optical path, and keeping mirrors and optical windows clear. Some of the techniques developed to achieve these aims will be discussed here.

With either liquid hydrogen or liquid deuterium as the Cerenkov medium, a deuterium-type condenser was used. That is, there was a liquid hydrogen reservoir which was used to condense the Cerenkov medium from gaseous hydrogen or deuterium. This arrangement (along with filters) not only insured the purity of the Cerenkov medium, but also made it possible to control the index of refraction accurately. The latter aim was accomplished by regulating the pressure of the condensing gas, typically at around 4 psig. To maintain constant pressure the regulator⁷ would either take more gas from the bottle or exhaust excess gas. About 100 ft³ a day was used in this process. When regulating deuterium, which at the same temperature is at a lower pressure than hydrogen, it was necessary to achieve stability by running the deuterium reservoir very full, to lower the condensing efficiency.

The index of refraction was monitored by continually measuring the temperature with platinum resistance thermometers immersed in the top and bottom of the stainless steel and Mylar flask holding the Cerenkov medium. Other thermometers monitored the temperature of the reservoirs. By means of the pressure regulation, the temperature was kept constant to $\pm 0.02^{\circ}\text{K}$, which corresponds to ± 0.00006 in index of refraction, or ± 0.02 deg in Cerenkov angle, which is to be compared with our ring aperture of ± 3 deg.

To maintain stability and reduce bubbling the Cerenkov medium was surrounded either by more of the same material (e.g., the liquid hydrogen or deuterium around the outside of the cylindrical mirror), or by the separate liquid hydrogen shield connected to the condensing system (Fig. 3). This in turn was enveloped in a liquid nitrogen jacket and separated from the outside world by a high vacuum system. Because of the large (12-in. diameter) optical aperture, heat gets into the flask, and bubbling must occur. To keep the bubbles out of the optical path, bubbling points are provided at convenient places, such as outside the cylindrical mirror. A bubble shield was also provided at the cylindrical mirror exit to conduct bubbles around the mirror edge. It will also be noticed in Fig. 3 that the counter window (and hence the following optical system) is tipped with respect to the horizontal counter axis to aid in the removal of bubbles or sediment from the exit window. In the smaller counter this exit window was on the side of the counter instead of the bottom, and such tilting was not required.

The hydrogen shield outside the flask served also to prevent condensation on the window and lenses. Despite liquid-nitrogen trapping during the initial diffusion pumping and then maintaining a vacuum of typically 5×10^{-8} torr using only an ion pump, material could collect on cold surfaces in the optical path. This was prevented by surrounding all such surfaces by liquid-hydrogen-cooled

shields which were always cooled before filling the flask. With the older counter which did not have such shields window fogging caused enough scattering of Cerenkov light into the anticoincidence ring to decrease counter efficiency by about 1% per day. No such effect was observed with the newer counters, when the shields were used properly.

IV. COUNTER PERFORMANCE

For the purposes of the pion lifetime experiment,² it was necessary that the counters' response be broader than the beam's limits in momentum ($\Delta p/p = \pm 0.5\%$) and in angle (± 0.6 deg), and yet they had to separate cleanly pions and muons of the same momentum. A ring aperture of ± 3 deg (for 11 deg Cerenkov light) satisfied these requirements, and a momentum-response curve for this aperture is shown in Fig. 4. This curve was obtained by measuring the counter efficiency as a function of beam momentum. Note that in that figure the percentage of muons and percentage of pions do not add to 100%, although the beam consisted solely of these two particles, electrons having been eliminated by another counter. Also one sees that the flat tops at the muon and pion peaks have slight slopes. Both of these effects are due to the variation of the π/μ ratio with momentum in the beam itself, and they both give the same value for this variation. The flat tops and steeply sloping sides (30% change in efficiency with 1% momentum change) indicate that the counter was both highly efficient and had a good rejection. An indication of the latter is the ratio of the pion peak to the valley on either side, and this is about $10^4:1$. The very deep dip on the high-momentum side of the pion peak occurs because Cerenkov light from pions of that momentum goes directly into the anticoincidence ring.

The excellent rejection of this counter is also apparent in the pulse-height distribution obtained when the counter is responding to pions which are required to go completely through the counter. One then gets a peak pulse height 500 times

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that of the valley and a shape corresponding to detecting about 80 photoelectrons. However, a very much poorer distribution results when the particle is not required to traverse the entire Cerenkov counter undeflected. Such a distribution with a peak-to-valley ratio of about 6 is shown as curve B of Fig. 5. This distribution results of course from the varying distances particles go with the proper velocity and direction in the Cerenkov medium before they interact. The problem of pion interactions in this counter was particularly acute because the momentum is near the peak of the $T = 3/2$, $J = 3/2$ first pion-nucleon resonance. At this momentum the π^-p cross section is only $1/3$ that of the π^+p and hence curve C(π^-) is much better than curve B(π^+) for distinguishing pions from background. It is primarily for this reason that we used liquid deuterium. Although the extra neutron produces more interactions and hence an even worse pulse-height distribution (Curve A), that distribution is identical for π^+ and π^- because of charge independence. Since in comparing π^+ and π^- lifetimes we had to avoid any charge-dependent bias, deuterium was used.

These interactions, which will be reduced considerably when the counters are employed for comparing K^+ and K^- lifetimes, were one of the two sources of trouble we had with the counter when it was used to detect the number of surviving π^+ or π^- particles. The other difficulty was the uniformity of response of the counter across its aperture. We have already discussed the possible effect of the 45 deg mirror, which turned out to be unimportant, but there was a non-uniformity which was traced to the 5-in. photomultipliers (RCA 4522). Despite some mixing of light ray directions by the lens and reflecting cone, there is a strong correlation between the position of the pion entrance to the Cerenkov medium and the position of the light on the photomultiplier face. The photocathode efficiencies were found to be highly nonuniform, resulting in counter efficiency changes of as much as 0.2% per inch, during some data taking. However, RCA at our urging

has now begun producing much more uniform tubes.

Despite a number of difficulties which had to be overcome, these liquid hydrogen or deuterium counters have arrived at a state of perfection in which limitations on stability and uniformity of response seem to be provided primarily by photomultiplier characteristics. They have been used successfully in one high-precision experiment, in which the π^+/π^- lifetime ratio was found to be 1.00064 ± 0.00069 , and they will soon be utilized in another.

FOOTNOTES

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5. The mirror was made from 0.0005-inch thick aluminized Mylar, specifically made for high reflectivity by the G. T. Schjeldahl Co., Northfield, Minn. The Mylar was stretched in a frame and attached to an elliptically-shaped stainless steel holder with Epoxy 828 and Versamid 140. The mirror for the

larger counter, the holder for which was 9 7/16-in. x 13-in. had to be made especially tight to prevent rippling at liquid hydrogen temperatures, and this was done by heating and tightening the Mylar in its stretcher frame just before bonding.

6. After testing many materials it was found that the quartz could be bonded to Kovar so as to stand many temperature cyclings if a mixture of Adiprene L-100 (100 parts) and Moca (12 1/2 parts) were used. These are DuPont products.
7. Bell-O-Fram pressure regulator, Model 10A.

FIGURE CAPTIONS

- Fig. 1 Experimental layout for the comparison of π^+ and π^- lifetimes in which two (CM and CP) liquid hydrogen or liquid deuterium Cerenkov counters were used. CM is a 4-in. diameter counter used to define the pion beam (along with coincidence counters M and anticoincidence counters A) and CP, a 7-inch diameter counter, moves along a track to measure the number of π^+ or π^- surviving as a function of distance.
- Fig. 2 Schematic drawing of the original liquid hydrogen differential Cerenkov counter. Note that the diameter of the ring focus depends on the angle of emission of the Cerenkov light (and hence the velocity of the particle), while the lateral position of the ring focus with respect to the ring aperture depends on the direction of the particle. The optically coaxial cylindrical mirror provides full efficiency across the 4-in. diameter of the radiator. LH₂: 4 x 8-in. long liquid hydrogen radiator. S: 1/4-in. sapphire window. M: 45-deg mirror. L₁, L₂: quartz lenses. Q: quartz vacuum window. A: ring aperture. LP: anticoincidence-ring light pipes. C: coincidence photomultiplier. A_R, A_L: anti-

coincidence photomultipliers. MC: cylindrical mirror.

Fig. 3 Movable liquid deuterium Cerenkov counter (CP). The optical system is similar to that of Fig. 2 except that the LD_2 flask has a 7-in. diameter and the exit window is at the bottom, out of the beam. Note the LH_2 (liquid hydrogen) shield surrounding the quartz lenses which cryo-pumped impurities onto itself and kept the flask quartz window free of condensation.

Fig. 4 Efficiency of the Cerenkov counter as a function of incident momentum. Note the pion and muon peaks and the deep valley between them.

Fig. 5 Typical pulse height distributions from CP when no requirement is made for the incident particle to traverse the counter. A is the distribution obtained with liquid deuterium and is identical for π^+ and π^- . B and C were obtained with liquid hydrogen in the counter for π^+ and π^- respectively.

Fig. 1

MUB 13658

Fig. 2

XBL683-2172

Fig. 3

XBL687 - 3161

Fig. 4

XBL685-2677

Fig. 5