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A Large Scintillator Array for Particle Identification by Time of Flight

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INTRODUCTION

The time of flight (TOF) system described here was constructed for the TASSO (Two Arm Spectrometer Solenoid) experiment (1, 2, 3) at the DESY e^+e^- Storage Ring PETRA. A major feature of this experiment is the ability to identify pions, kaons and protons over a wide momentum range. The TOF system forms part of this facility, providing π -K separation up to a momentum of 1.1 GeV/c and $(\pi/K)_p$ separation up to 2.2 GeV/c (~ 3.5 S.D. separation).

The time of flight of particles is measured over a flight-path of approximately 5.7m between the e^+e^- interaction point and the scintillation counters of the TOF array. However, at a point approximately one third of the way along the flight-path, the particles pass through a considerable amount of material, most of which is the 1-radiation length aluminium coil of the TASSO magnet. This introduces several problems into the particle identification.

In section 1 we describe the separate components of the TOF system. The calibration of the device is contained in section 2. In section 3 we discuss the various factors introduced by the TASSO coil and the long particle flight-path while section 4 summarises the contributions to the timing resolution. Section 5 contains some first results from the TASSO experiment.

1 THE TOF EQUIPMENT

A diagram of the TASSO apparatus is shown in Fig 1. The central detector which is inside the solenoid coil of the 0.5T magnet has been described previously (2, 3) and is filled with tracking chambers (4) which provide momentum and direction measurements of tracks produced by e^+e^- interactions at the centre of the beam pipe. On either side of the central detector and perpendicular to the beam line are the two particle spectrometers (called hadron arms) which contain, in addition to the TOF array, planar drift chambers, Cerenkov counters, lead-scintillator shower counters and an iron absorber behind which are proportional tubes for muon detection. The central half of each TOF array is parallel to the beam line.

A LARGE SCINTILLATOR ARRAY FOR PARTICLE IDENTIFICATION

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ABSTRACT

We describe the design and method of operation of a large scintillator array used for particle identification by time of flight. The calibration of the array and the consequences of having approximately 1.1 radiation lengths (210 cm) of aluminium in the particle flight-path are described in detail.

while the wings of the array are bent inwards by 19 degrees to increase slightly the solid angle acceptance. The array in each arm consists of 48 separate scintillators (1.6m high and 33cm wide, made from Nuclear Enterprises NE110) and arranged in two rows of 24, one above the other, forming walls of scintillator in each arm 5.2m high and approximately 8m wide, which together cover 20% of the solid angle.

The dimensions of the scintillators and light-guides are shown in Fig 2. The light-guides (5) (made from normalised perspex and designed by G L Salmon and R J Barlow of the TASSO collaboration) are glued to the scintillators by optical cement and have a uniform acceptance for light collection across their widths. At each end of the counters is an EMI 9807B photomultiplier tube in optical contact with the light-guide by means of a silicone rubber disc compressed by a spring. The disc is made from Rhodorsil RTV121 and is 50mm in diameter and 3mm thick.

The choice of the EMI 9807B photomultiplier tube for this experiment was made on the basis of results with a prototype counter in a test beam. Also considered was the RCA 8575R which is interchangeable with the 9807B. Other, more expensive tubes from other manufacturers, while having marginally better timing resolution, were not considered on cost grounds.

Fig 3 shows the voltage divider (designed by G L Salmon of the TASSO collaboration) used with the 9807B photomultiplier tube. The total potential difference between photocathode and anode is typically 2.4kV, stable to $\pm 4V$, (equivalent to approximately 40 psecs time drift after pulse height correction). The photocathode-first dynode potential difference is made large to optimise the timing resolution. The high voltage setting of each tube was obtained by comparing the gain with the gains of a set of well known reference tubes. Both the manufacturer's gain measurements and our own laboratory measurements were used to arrive at an operating high voltage for each tube. The spread in operating high voltage is less than $\pm 150V$.

The anode signal from each photomultiplier travels along 22.7m of RG214 double-shielded 50 Ohm cable to a resistive splitter, as shown in Fig 4. The attenuation down the 22.7m is only 8%. About 85% of the pulse height

(which is $\sim 1V$ for a minimum ionising track entering the scintillator close to the photomultiplier and $\sim 300mV$ for a hit at the far end of the counter) is sent to a leading edge discriminator (LRS 6208L) set at a discrimination level of 80mV while the remainder goes to a charge integrating ADC (LRS 2282). The splitter is AC-coupled into the ADC to reduce low-frequency pickup. The discriminator supplies a stop for a TDC and also sets a latch bit which, if set, causes readout of the contents of the TDC by the online computer after digitisation is complete. A third output goes to a meantimer system (LRS 624) and an RL 608 majority logic unit (6) used to provide test triggers for other hadron arm equipment. The contents of the ADC (to which about 15% of the pulse height is sent) are used to compute pulse height corrections to the timing. This method of timing, by making offline pulse height correction, is less expensive but is not capable of as good an ultimate resolution as methods involving multiple discrimination levels.

The start for the TDC is provided by a signal from an electrostatic pickup inside the PETRA beam pipe (7). PETRA contains bunches of electrons and positrons approximately 3cm in length. Every e^+ beam crossing (every 4 microseconds) the pickup delivers a fast (≤ 1 nanosecond) bipolar pulse which is discriminated and fanned out to the whole experiment and which generates the TDC start and the gate for the ADC and latch boxes. If the TASSO trigger logic decides on the basis of information from elsewhere in the experiment that the TOF TDCs and ADCs should be readout by the online computer, then strobes from subsequent beam crossings are inhibited until the data-acquisition is ready for the next event. If it is decided that the crossing is not of interest then a 'fast clear' is issued a constant 1 microsecond before the next usable beam crossing. This one microsecond does not allow the TDCs to resetttle exactly to zero counts. However, if a constant resettling time is applied then the TDCs return to constant values (in this case ~ 4 least counts to within ± 1 least counts). In the early part of the experiment the beam crossing strobe was derived from the pickup signal after simple attenuation and discrimination by a leading edge discriminator. This resulted in a 'time walk' of the order of 100-200 picoseconds over the lifetime of a stored beam in PETRA during which the current in the e^+ beam and consequently the size of the induced

electrostatic signal decreases by about 3. This time walk is, of course, unknown event by event and compounds the intrinsic resolution of the counters. Recently, however, the situation has been improved by using a special zero-cross discriminator built at the Rutherford Laboratory (8) designed to handle such fast pulses, and which has a corresponding time walk of 50-100 picoseconds.

An aid in checking the array of counters is given by a system of light-emitting diodes. The perspex block on each light guide (Fig 2) holds a green light diode (Telefunken type CQY 86) which gives a slow (≥ 10 nsecs) rise-time but large ($\sim 3V$) photomultiplier pulse. All the light diodes are pulsed from a single mercury pulser (at 50Hz), the high voltage pulse from which is fanned out using a coaxial transformer (no power loss) circuit (designed by H L Lynch and J Freeman of the TASSO collaboration). Light diode data are taken every day and are used to check for electronic faults and to provide a rough check on timing, being stable to ± 200 picoseconds.

2 CALIBRATION

In this section we discuss the items necessary for calibration of the TOF system. These comprise: (2.1) an understanding of the gains of the TDCs and ADCs; (2.2) a determination of the timing variations from channel to channel which come from small differences in cable lengths (this is done with the aid of a spark gap - optical fibre system) and (2.3) a computation of the pulse height correction and the overall timing offset in each of the two hadron arms.

2.1 ADC AND TDC GAINS

As described in section 1, the anode pulses from each photomultiplier tube are split unequally, to an ADC and to a discriminator for a TDC stop. The ADC used in this experiment (LRS 2282) has a gain of 0.25 picocoulombs/least count and a full range of 4000 least counts although only the lower 25% of the full range is used where the gain is linear and the channel-to-channel variation in gain is $< 10\%$ of the nominal gain. This is measured and periodically checked with a Camac-controlled DAC.

Most of the TDCs used for the TOF array are LRS 2228As although some ORTEC TD811Ss are also used. Each has a nominal gain of 50 picoseconds/least count and a full range of 100 nanoseconds. With the modules in place in the experiment the gains must be periodically measured for each channel and any deviation from the nominal gain recorded for offline correction. For these measurements we use a test circuit, the main component of which is an ORTEC 462 time calibrator. Delay cable is added to ensure that our timing measurements do not fall in the highly non-linear bottom $\sim 10\%$ of the TDC dynamic range.

2.2 SPARK-GAP - OPTICAL FIBRE SYSTEM

The channel-to-channel timing variations for the TOF array are determined using TDC data from a spark-gap. Fig 5 shows our spark-gap, the design for which was based on that of the I Physikalisches Institut der RWTH Aachen for the TASSO Inner TOF system. The choice of series resistance (400 M Ω m) and self-capacitance of the gap (about 25 pF) gives a spark rate of about 50-100 Hz. The two gaps, one for each arm, run in nitrogen at 2.5 atmospheres overpressure (the high pressure providing stability of the spark) and contain 96 viewing windows for the 96 fibres in each arm.

The windows are carefully aligned to point each fibre accurately at the spark and a neutral density filter is chosen to supply a suitable amount of light for the photomultipliers. Each fibre (Rank Fibroflex Type 1) is 12m long and enters the light guide as shown in Fig 2, 30cm from the tube. The size of the gap is chosen to deliver an amount of light such that a fast (~ 2 nsecs rise time) large ($\sim 3V$) pulse is obtained from the tube allowing relative channel timings of ± 100 psecs which is stable to 2 or 3 least counts over many weeks. The 50 Ohm cable which completes the spark-gap high voltage circuit carries a fast (~ 2 nsecs FWHM) pulse which after considerable attenuation (about 40 db) provides a TDC start in similar fashion to the beam crossing signal. Spark-gap data are taken throughout each running period.

In the first instance we have assumed that the 96 fibres attached to the spark gap in each arm deliver light to the photomultiplier tubes at the same time. Any differences in TDC measurements are then due to differences in the anode cables or the stop circuit electronics. The absolute timing offset of every channel in each arm is then expressible in

terms of the (as yet unknown) overall timing offset of the hadron arm plus the spark-gap corrections. The assumption of equal timing for all fibres will not be exactly correct. This situation can be rectified by collecting for each channel a large sample of clean tracks from well reconstructed e^+e^- interactions and then by making fits for each counter of the sort at present made for each arm, as described below. So far we have not collected enough data to do this. It is conceivable therefore that there are timing differences between channels of an estimated ± 0.2 nsecs. Our analysis of the first data from TASSO, described in section 3, shows that the differences are not larger than this.

2.3 PULSE HEIGHT CORRECTION

The measured timing ('T') of a particle we have found to be adequately described by:-

$$T = \tau + A Q_1^{-1/2} + YV + B$$

where ' τ ' is the real flight-time, 'Q' is the integrated charge measured by the ADC, 'Y' is the distance from the hit in the scintillator to the tube, and 'A' (the pulse height correction factor), 'V' (the effective inverse velocity of light in the scintillator) and 'B' (the absolute timing offset) are to be determined. This parameterisation has been used in previous experiments (9), and has been studied for our configuration both in test beams and in position in the TASSO experiment. The ADC correction combining the two ends $A(Q_1^{-1/2} + Q_2^{-1/2})/2$ is typically 2 nanoseconds.

In general, the parameters 'A' and 'V' are highly correlated. However, a study with a prototype counter in a test beam showed that if a constant value of 'A' was taken for all 'V' then an approximately constant velocity of light was obtained.

Of the 96 scintillators in the experiment, ten were tested using an 18 MeV electron beam from a Betatron. A search was made for unexpected differences between scintillators (we found none) and a study made of the optimum high-voltage settings of the tubes and discrimination levels prior to installation.

Figs 6(a) to (c) describe for one counter the tests made on velocity of light, average integrated charge and timing resolution. In this case, the EHT settings and discrimination levels were as used in the experiment. The superimposed curves for attenuation length and resolution show 'typical' values for this batch of counters. The resolution is seen to degrade slowly with distance from the tube. Also there is a slight degradation close to the tube caused by the discrimination level moving into the beginning of the pulse which is sensitive to single photoelectrons.

With the scintillators in place in the TASSO experiment, the parameters 'A' and 'V' have been determined for each channel using the low flux of (> 1 GeV/c) horizontal cosmic rays (mostly muons) recorded during PETRA data taking, and by making fits to:

$$T_1 - T_2 = A [Q_1^{-1/2} - Q_2^{-1/2}] + V [Y_1 - Y_2]$$

where the suffices '1' and '2' refer to the two ends of the same counter. The minimum momentum of 1 GeV/c ensures that there is little multiple scattering in the coil. Also we require timings similar to the timing of particles in real e^+e^- interactions. Using a sample of approximately 200 tracks per counter, we found that 'V' and 'A' determined for all counters are the same within errors. In subsequent analyses we have fixed 'V' and 'A' at:-

$$V = 1.27 \text{ TDC least counts/cm}$$

$$A = 560 \text{ TDC least counts, (ADC least counts)}^{1/2}$$

The final quantity to fix is the overall timing offset ('B'). To do this we take all tracks which come from the e^+e^- interaction point, which are all well reconstructed in the central detector and which cannot be confused with other tracks at their intersection point with the TOF array. We do not use the large number of e^+e^- elastic scatters (Bhabha events) as electrons shower considerably in the coil and have unreliable TOF information. We then invoke an iterative procedure which uses the fact that the majority of these tracks will be pions. In the first iteration we assume all tracks to be pions which fixes 'B' only to about 500 picoseconds but from which it is possible to define a better pion sample. After approximately three more iterations a consistent value of 'B' is obtained. This fitting procedure is made for each hadron arm for every

two or three weeks of data taking, or if the experimental setup changes in some way. The data sample consists typically of 250 tracks per hadron arm which is sufficient to fix 'B' to ± 100 picoseconds.

3 CONSIDERATIONS ARISING FROM THE TASSO COIL AND THE LARGE PARTICLE FLIGHT-PATH

Particles which are produced in e^+e^- interactions and which are detected in the TOF array must have passed through the central detector (which measures momentum and angles) and have penetrated the coil of the TASSO magnet experiencing energy loss and multiple scattering on the way through. The total amount of material traversed by the particle is always greater than the 28 gm/cm^2 of aluminium in the coil and its heatshield plus an additional 2.5 gm/cm^2 of 'equivalent aluminium' in the Cerenkov counters. In sections 3.1-3.3 we consider the contribution to the overall resolution of the detector from the three factors: track reconstruction, energy loss and multiple scattering.

In addition, in order to compute the rate at which different types of particles are produced, we must correct for the interaction probability in the coil. This is typically 25%, although momentum and particle dependent (10). The loss of tracks by decay in flight, important only for kaons, is described in Fig 7, where a Monte Carlo generated kaon momentum spectrum (for e^+e^- annihilations at a cm energy of 30 GeV) is shown together with the number of kaons which survive to reach each component in the hadron arms. Energy loss in the coil means that more particles will decay in the hadron arms than would otherwise have been the case. Fig 7 also shows the overlap for $K^\pm$ of the Hadron Arm TOF (HTOF) counters with the TASSO Inner TOF (ITOF) counters and the thresholds (for $\pi^\pm$) of the three Cerenkov counters (11).

3.1 TRACK RECONSTRUCTION

Nominal errors for track reconstruction in the central detector are:

$$\begin{aligned}\Delta p_T &\sim 0.02 p_T^2 \quad (p_T \text{ in GeV/c}) \\ \Delta\phi &\sim 4 \text{ mrad} \\ \Delta\lambda &\sim 7 \text{ mrad}\end{aligned}$$

Here, ' p_T ' is the momentum measured in the plane perpendicular to the beam direction (z), ' ϕ ' is the azimuthal angle in this plane measured at the outer edge of the central track chambers and ' λ ' is the dip angle of the track out of this plane. $\Delta\lambda$ is larger than $\Delta\phi$ because of the small ($\sim 4^\circ$) angles of the stereo wires of the TASSO drift chamber. Over a 5.2m flight-path, the $\Delta\lambda$ results in a $\Delta z \sim 5\text{cm}$ comparable to the z positional resolution of the TOF counters themselves. The Δp_T and $\Delta\phi$ errors are negligible compared to other factors for the momentum range in which the TOF counters are useful. For example, at 1GeV/c a π ($\beta = .99$) and a K ($\beta = .89$) have an error on β , ($\Delta\beta$), from the Δp_T of only .0004 and .004 respectively.

3.2 ENERGY LOSS

The flight-time of a particle depends on its velocities before and after the coil. For a pion with momentum above 0.6 GeV/c , the momentum loss in the coil is only about .04 GeV/c not appreciably affecting a flight-time calculation. However, for the more massive kaons and protons the momentum loss is greater. Kaons of momentum $\lesssim 0.4 \text{ GeV/c}$ and protons $\lesssim 0.6 \text{ GeV/c}$ will not penetrate the coil. Even at 1.1 GeV/c , the result of a calculation of the proton mass using TOF information but neglecting energy loss would change the calculated proton mass to $m = 1.0 \text{ GeV/c}^2$.

Particle assignments (ie π , K or p) are made to tracks by comparing the measured flight-time, ' t ', with the flight-times expected for the different particle types. A knowledge of the correct energy loss for each type is essential for this. The effect of energy loss alone (without multiple scattering) is actually beneficial to the particle separation ability of the detector as at the same momentum a heavier particle has a greater energy loss. This effect is illustrated in Fig 8 where the β of each particle as a function of momentum is compared to the effective value of β (β_{eff}) if energy loss is disregarded from the calculation.

3.3 MULTIPLE SCATTERING

The trajectory of a particle in the hadron arms is inferred by extrapolation from its reconstruction in the central detector. Fig 9 shows a distribution of the difference between the counter which is hit and the counter predicted

by extrapolation. The distribution has a standard deviation of ~ 7 cm (~ 0.6 counters, with a counter 33cm wide in the beam-line direction (z)) which comes from multiple scattering and the errors in reconstruction. As the latter is small, the size of the multiple scattering in the z direction is then calculated simply by knowing which counter was hit (to within the width of one counter). In the vertical direction (y), however, no information is available except the relative timings of the two photo-multipliers. The rms multiple scattering, allowing for energy loss, for a particle passing through material of radiation length ' L_0 ' is given by:-

$$\theta_{\text{rms}} = \frac{0.015 (1 + \epsilon)}{\sqrt{m} \Delta L_0} \sqrt{\log \left[\frac{(E_0 - m)}{(E_i - m)} \frac{P_i}{P_0} \right]} \text{ radians}$$

where ' E_i ', ' P_i ' and ' E_0 ', ' P_0 ' are the energy and momentum before and after the coil respectively, ' m ' is the particle mass (GeV/c^2), ' Δ ' is the minimum energy loss for aluminium (0.00437 GeV/cm) and $\epsilon \sim 0.1$. The rms scattering in the y direction is then

$$\sigma_y = \theta_{\text{rms}} L^H$$

where ' L^H ' is the pathlength in the hadron arm. For a pion at $1 \text{ GeV}/c$ this is about 8cm, or a timing shift in each tube from that expected of about 0.5 nsecs. If information is available from both phototubes then the effect is not too critical as the times from the two ends can be compared to see if the y position predicted by the relative timing of the two tubes is consistent with the extrapolated y position. However, if information is available from one tube only (for example, through tube inefficiency) then there will be a shift in the flight-time calculation for that track. Also the total length of the particle flight-path will not be computed correctly.

Fig 10 shows the calculated contribution to the resolution of the TOP system from multiple scattering alone. The rapid degradation in resolution towards low momentum for kaons and protons is a major limiting factor at these momenta.

An improved flight time and entry point in the scintillator can be obtained by forming the chi-square:-

$$\chi^2 = \left(\frac{\tau - t_1 + yV}{\sigma_1} \right)^2 + \left(\frac{\tau - t_2 + V(D-y)}{\sigma_2} \right)^2 + \left(\frac{y - y_m}{\sigma_y} \right)^2$$

where ' t_1 ', ' t_2 ' are the measured times at the two ends after pulse height correction, ' y ' is the distance from end 1 at which the track entered the scintillator, ' D ' the length of the scintillator (260cm) and ' y_m ' is the extrapolated entry point. The errors σ_1 and σ_2 are the timing resolutions of the tubes at the two ends (and are a function of ' y ') while σ_y is the projected multiple scattering error in the ' y ' direction. Choosing a ' y ' such that the chi-square is least yields an estimate of the flight-time ' τ '. Fig 11 shows a confidence level distribution from the chi-square for a large sample of tracks entering the TOP array. Selecting tracks in different momentum ranges or in different positions in the counters renders us more sensitive to the individual uncertainties involved. However, all the confidence level distributions so obtained are acceptably flat.

4 RESOLUTION OF THE TOP SYSTEM

Fig 12 describes (as a solid line) the resolution obtainable with the TOP system if the resolution of each tube were as described in section 2 for test beam measurements. To obtain this resolution a weighted mean is taken using the measured times and individual known resolutions of the two tubes. An estimated additional jitter of 0.2 nsecs from fluctuations in the start pulse has been added in quadrature. If a simple average of times from the two ends is taken then a resolution described by the dotted line results. It can be seen that the two methods give very similar values except close to the ends. For physics analysis we have chosen the simple average method as with this we are less sensitive to the systematics of the spark-gap correction uncertainties.

Combining this intrinsic resolution of the TOP system with multiple scattering and the various other effects gives the overall resolution of the detector shown in Fig 13. For pions or kaons with momentum $> 1 \text{ GeV}/c$ the timing resolution will be on average ~ 0.53 nsecs. The same value is obtained for pions $> 0.35 \text{ GeV}/c$ but is considerably worse for kaons $< 1.0 \text{ GeV}/c$. Although there is considerably worse resolution at lower

momentum, the flight-times for different particle types diverge also (Fig 14). Fig 15 shows the resolution calculated from the timing difference between the measured flight-time and the time expected for a pion or a kaon (whichever is better) for tracks with momentum (0.8-1.2) GeV/c using tracks from e^+e^- annihilation events. In this momentum region the flight-time difference between π^+ and K^+ is large compared to the resolution, and multiple scattering and other factors are of less importance. The observed resolution is ~ 0.65 nsecs slightly larger than that expected for a mixture of π^+ and K^+ .

An additional check comes from studying the timing of muons produced in the reaction $e^+e^- \rightarrow \mu^+\mu^-$ where each muon has momentum greater than 4 GeV/c and is identified in the muon chambers. These tracks have multiple scattering ≤ 1 mrad and are measured by the central track chambers better than the average hadron in a complicated $e^+e^- \rightarrow$ hadron event. Fig 16 shows the difference between the measured and the expected timings for these muons. The resolution is 0.51 nsecs. These events also provide a check on the efficiency of the counters which has been measured to be 97% for a single tube averaged over the whole array.

5 RESULTS FROM THE TASSO EXPERIMENT

Fig 17 shows a distribution of p_{eff} as reconstructed from TOF information as a function of momentum as measured in the central detector. Clear pion, kaon and proton bands are visible. Although the events from which these tracks are taken all come from within ± 10 cm of the nominal e^+e^- interaction point, about half of them are beam-gas interactions, so enhancing the proton signal. A small number of baryons are produced in real e^+e^- annihilations and a study of their rate of production and a comparison with pion and kaon production has already been published (12).

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REFERENCES

- (1) A proposal for a large 4π Magnetic Detector at PETRA: TASSO Proposal, PPSP/76/34
- (2) TASSO Collaboration: R Brandelik et al, Phys Lett 83B (1979) 201
- (3) Members of the TASSO Collaboration are:-
 R Brandelik, W Braunschweig, K Gather, V Kadansky, K Lübelmeyer, P Mättig, H -U Martyn, G Peise, J Rinkus, H G Sander, D Schmitz, A Schultz von Dratzig, D Trines, W Wallraff (AACHEN): H Boerner, H M Fischer, H Hartmann, E Hilger, W Hillen, L Koepke, H Kolanoski, G Knop, P Lev, B Löhr, R Wedemeyer, N Wermes, M Wollstadt (BONN): H Burkhardt, D G Cassel, D Heyland, H Hultschig, P Joos, W Koch, P Koshler, U Kötz, H Kowalski, A Ladage, D Lüke, H L Lynch, C Mikenberg, D Notz, J Pyrlík, R Riethmüller, M Schliwa, P Söding, B H Wiik, G Wolf (DESY): R Fohrmann, M Holder, G Poelz, O Römer, R Rüsck, P Schmüser (HAMBURG): D M Binnie, P J Dornan, N A Downie, D A Garbutt, W G Jones, S L Lloyd, D Pandoulas, J Sedgbeer, S Yarker, C Youngman (IMPERIAL COLLEGE, LONDON): R J Barlow, I Brock, R J Cashmore, R Devenish, P Grossmann, J Illingworth, M Ogg, B Roe, G L Salmon, T Wyatt (OXFORD): K W Bell, B Foster, J C Hart, J Proudfoot, D R Quarrie, D H Saxon, P L Woodworth (RUTHERFORD LABORATORY): Y Eisenberg, U Karshon, D Revel, E Ronat, A Shapiro (WEIZMANN INST): J Freeman, P Lecomte, T Meyer, Sau Lan Wu, G Zobernig (WISCONSIN).
- (4) H Boerner et al, DESY 80/27 (1980), submitted to Nuclear Instruments and Methods
- (5) Light Guide Design for Large Time-of-Flight Systems: R J Barlow et al, Oxford University Internal Report
- (6) RL (Rutherford Laboratory) 608 Description. The RL608 is a 48-way fanin.

- (7) H Frese et al, IEEE Transactions on Nuclear Science, Vol NS-24, No 3, June 1977
- (8) D J White, Rutherford Laboratory Report RL-80-006 (1980)
- (9) W Braunschweig et al, Nucl Inst Methods 134 (1976) 261
- (10) We have calculated interaction cross sections in aluminium from the following publications:-
 E S Miller, Thesis Princeton University, 1967
 Allardyce et al, Nucl Phys A209 (1973) 1
 Crozon et al, Nucl Phys 64 (1965) 576
 Binon et al, Nucl Phys B17 (1970) 168
 Renberg et al, Nucl Phys A183 (1972) 81
 L Ray, Phys Rev C20 (1979) 1857
 Abrams et al, Phys Rev D4 (1971) 3235
- (11) P Lecomte, Invited Talk at the International Conference on Experimentation at LEP, Uppsala, Sweden, June 1980
- (12) TASSO Collaboration, R Brandelik et al, DESY 80/49 (1980)

FIGURE CAPTIONS

- (1) Plan view of the TASSO detector.
- (2) Components and dimensions (in mm) of each time of flight counter.
- (3) Voltage divider used with the EMI 9807B photomultiplier tube.
- (4) Electronic logic associated with each time of flight counter.
- (5) Nitrogen spark-gap used for timing calibration of the TOF array.
- (6) Tests made for one particular counter on (a) attenuation length
 (b) variation of resolution with position in the counter and
 (c) uniformity of the velocity of light in the counter.
- (7) A Monte Carlo generated momentum spectrum for $K^{\pm}$ together with the number of kaons which survive to reach each component in the hadron arms (not including the 20% geometric acceptance of the hadron arms). Also shown are the useful momentum ranges for $K^{\pm}$ identification for the two sets of TASSO time of flight systems and the thresholds (for pions) of the three Cerenkov counters.
- (8) Velocity (β) of each particle as a function of momentum (dotted line) with the β_{eff} due to energy loss in the coil (solid line).
- (9) Distribution of the difference between hit counter and counter predicted by extrapolation from the central detector. Each counter is 33cm wide.
- (10) Contribution to the resolution of the time of flight system from multiple scattering averaged over the array.
- (11) Distribution of confidence level for a fit to the vertical coordinate at entry to the scintillator (including uncertainties from multiple scattering) as described in the text.
- (12) Timing resolution of each counter from the photomultiplier tubes alone if an average of the time from the two tubes is taken (dotted line) or if a weighted mean is made (solid line). An additional jitter of 0.2 nsecs has been added in quadrature.
- (13) Resolution of the time of flight system averaged over the array for each particle type as a function of momentum.
- (14) Difference in flight-time over a flight-path of 570 cm for two particle types as a function of momentum.
- (15) Timing differences between the measured flight-time and the time expected for a pion or a kaon (whichever is better) for tracks with momentum (0.8-1.2) GeV/c.
- (16) Difference of expected and measured timings for identified muons from the reaction $e^+e^- \rightarrow \mu^+\mu^-$.
- (17) Distribution of β_{eff} for recent TASSO data.

TASSO

(a)

(b)

(c)

TIME EXPECTED - TIME MEASURED (nsec)