CA8407177

TRI-PP-83-63
Aug 1983

THE TRIUMF LOW ENERGY PION SPECTROMETER AND CHANNEL[+]

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Abstract

A low energy pion spectrometer has been developed for use with the TRIUMF M13 pion channel. The combined channel and spectrometer resolution is presently 1.1 MeV at T = 50 MeV. This is limited by the amount of gas and detector material in the spectrometer in addition to the inherent resolution of the channel. Improvements to both the spectrometer and channel are discussed.

(submitted to Nuclear Instruments & Methods)

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[+] Research supported in part by Natural Sciences and Engineering Research Council of Canada

1. Introduction

Pions and their interaction with nuclei have become an area of interest in nuclear structure, nuclear matter, heavy ion collisions and nuclear astrophysics [1]. However, specific study requires an understanding of how the pion interacts with the nucleus. One of the most direct methods for investigating the pion-nucleus interaction is to scatter pions from nuclei. Experimental programs using high resolution pion spectrometers at SIN [2] and at LAMPF [3] have studied this interaction by elastic and inelastic pion scattering near the $\Delta(3,3)$ resonance. In the operational regime of these spectrometers (P_π = 120-560 MeV/c) the (3,3) resonance is dominant and the incident pion does not penetrate past the nuclear surface. At lower energies ($T_\pi < 75$ MeV) the pion can penetrate into the nuclear interior. Thus a low energy pion can probe properties of nuclear matter such as true pion absorption [4,5,6] and nuclear shapes [7,8].

In the past few years low energy positive pion elastic and inelastic scattering experiments were done with plastic scintillator [9,10], NaI [8,11] and Ge [12] telescopes. The detection of negative pions requires a different technique, since when a negative pion enters a large detector it is stopped, captured into an atomic orbit and subsequently absorbed. The absorption liberates the pion mass energy giving a complicated signal in a NaI or Ge detector. Instead negative pions were detected with scintillator range telescopes that measure the energy loss and range of the pion as it passes through a large number of thin scintillators [13,14]. Energy resolution of these systems is limited to ~2 MeV by energy straggling and a comparison of positive and negative pion scattering data is difficult. Clearly a magnetic spectrometer with high resolution and identical detection efficiency for both negative and positive pions would improve the quality of existing elastic scattering data and expand upon the limited amount of inelastic data. Magnetic spectrometers previously used for detecting low energy pions have been restricted by their small solid angles [15,16]. For these reasons the TRIUMF QQD low energy pion spectrometer was constructed.

The design of the QQD spectrometer was determined by the requirements of the experimental programme [17,18]. Energy resolution to resolve excited states (<300 keV), a broad momentum acceptance and a large solid angle are ultimately required. In addition the short decay length of the pion at low energies demands that the spectrometer have a short path length. It was found that the minimum number of elements needed to fulfill these requirements is three: a quadrupole doublet followed by a dipole magnet. No higher-order corrective elements have been installed. Instead the detection system incorporates four multiwire proportional counters to determine the momentum by ray-tracing the particle trajectories. The nominal design acceptance of the spectrometer is 20 msr for target spot sizes of ±15 mm radially and ±10 mm axially. The momentum acceptance is $\Delta p/p = \pm 10\%$ for pion momenta less than 150 MeV/c.

The spectrometer is situated in the M13 low energy pion channel at TRIUMF [19]. This beam line can be operated in either a doubly achromatic mode or in a dispersed mode. Higher-order elements have been installed to correct some of the chromatic aberrations in the channel so that its full acceptance can be utilized.

The specifications of the spectrometer and the pion channel are listed in table 1. In the following two sections the layout of the channel and spectrometer are described. The detection system is discussed in sect. 4 and the final section describes the performance of the system.

2. The M13 pion channel

The M13 beam line at TRIUMF is a low momentum (20-130 MeV/c) pion and muon channel [19]. It views the TRIUMF 1AT1 production target at 135° with respect to the primary proton beam. The layout of the channel and spectrometer is shown in fig. 1. It consists of two quadrupoles (Q1,Q2) and a right 60° bend (B1) to the first intermediate focus F1 where one set of momentum-defining slits is located. A field lens consisting of a quadrupole triplet (Q3,Q4,Q5) with a sextupole at the entrance (SX1) and exit (SX2) is located between the intermediate foci F1 and F2. A second set of momentum-defining slits is located at F2, followed by a left 60° bend (B2) and two more quadrupoles (Q6,Q7) which focus the beam on the scattering target.

The channel is normally run in a doubly achromatic mode. The magnification at F1 and F2 (with respect to the production target) is -0.90 and +0.90 with momentum dispersions of +1.26 and -1.26 cm/%, respectively. The momentum resolution of the channel is limited by the finite production target size. Typically available 10 mm and 2 mm carbon targets would result in resolutions $\Delta p/p$ of 5×10^{-3} and 10^{-3}, respectively. The fluxes for 50 MeV pions (128 MeV/c) for a $\Delta p/p = 1\%$ channel acceptance and primary proton beam of 500 MeV and 100 µA on a 10 mm carbon production target amount to 2×10^{6} π^{+}/s and 3×10^{5} π^{-}/s.

In order to improve the channel, second- and higher-order aberrations were investigated by TRANSPORT [20] and REVMOC [21] calculations.

One of the largest aberrations is the T_{126} or $(x/\theta\ \delta)$ term at the dispersed intermediate focus F2. This causes a severe tilt of 81° from the normal in the momentum focal plane. From the optics calculations it was determined that positioning two sextupoles at points after F1 and prior to F2 (preserving the midplane symmetry of the channel) could reduce this tilt of the focal plane to less than 1°. As a result two sextupoles were constructed and installed in the indicated positions (see fig. 1).

The full momentum acceptance of the channel was utilized by finding tunes where the pion beam could be dispersed across the scattering target. TRANSPORT calculations demonstrated that a variable negative dispersion (0 to -3.0 cm/%) is obtained at the scattering target if the quadrupole strength in Q3 is increased and Q5 is decreased (and vice versa for a positive dispersion). These adjustments do not affect the focus at F2 and the target; however, the magnification and the dispersion at these points are modified.

3. Optical layout of the QQD spectrometer

In fig. 2 a schematic view of the spectrometer optics in the radial plane is shown. The first quadrupole QT1 focuses in the bend plane while QT2 defocuses. The particles are then bent through 70° to the left in the scattering plane. The focal plane of the spectrometer is beyond the last wire chamber and is tilted at an angle of 72°. The layout of the spectrometer was influenced by the availability of a circular dipole magnet and a narrow Collins type quadrupole. The requirements of optimum resolution and maximum geometric acceptance were fulfilled by the two optical criteria: the sine-like (x/θ or R_{12}) function [20] should have a maximum inside the dipole magnet, and the beam should have an axial waist in the centre of the dipole magnet. This is readily accomplished by using two independent quadrupoles in front of the dipole magnet. Details of other solutions can be found in ref. [17].

The first-order momentum resolution (R) of the spectrometer is given by

$$R = \frac{p}{\Delta p} = \frac{1}{2x_0} \cdot \frac{D}{M} ,$$

where D the dispersion and M the magnification at the focal plane are 1.06 cm/% and −0.54 respectively; and x_0 is the radial size of the beam spot at the target. The size of the target spot is given by the uncertainty of the target spot position x_0, which is approximately ±1.0 mm. Thus the momentum resolution is approximately $R = p/\Delta p = 1000$. However, this cannot be achieved at present because of multiple Coulomb scattering in the windows and gases of the wire chambers inside the spectrometer.

In order to trace the path of a pion through the spectrometer and thus determine its momentum, the transfer coefficients from each of the wire chambers (WC) to the scattering target must be determined. The position r_i of a particle at the i-th wire chamber is given by

$$r_i = \sum_j (r_i|x_j)x_j + \sum_{jk} (r_i|x_j x_k)x_j x_k + \cdots ,$$

where x_i is one of the initial target coordinates $(x_0, \theta_0, y_0, \phi_0, \delta_0)$ in TRANSPORT formalism and $(r_i|x_j)$ and $(r_i|x_j x_k)$ are first- and second-order transfer coefficients respectively. These coefficients are measured experimentally using a wire mask mounted in the target location. In a scattering experiment the x-coordinates and y-coordinates of the four wire chambers along with these coefficients are used in a non-linear least squares routine to determine all five target coordinates (including the particle's momentum). This technique is similar to that used for other large solid angle spectrometers [22].

4. Detection system

Spectrometer systems are designed in one of two modes. In the first mode the spectrometer has precisely shaped magnetic fields corrected for most aberrations and a single detector located in the focal plane. In the second mode the spectrometer magnetic field may have higher-order components but several detectors are used to determine the particle's trajectory and momentum. There are two constraints for pion spectrometers: the pion flux is limited so the spectrometer must have a large solid angle, and the pion is short-lived ($\tau = 26$ ns) so the spectrometer path length must be as short as possible. A spectrometer of the second type was chosen to satisfy these criteria.

The positioning of the four wire chambers is shown in fig. 2. The locations of the wire chambers were chosen to maximize position and angular resolution. The two chambers before the dipole could only be located in two of three positions. The best first-order position and angular resolution of the initial target coordinates were obtained when the front wire chambers were located in position WC1 (prior to QT1) and WC3 (after QT2) [17]. The position resolution of the wire chambers in the horizontal plane is ±0.5 mm yielding errors of ±0.7 mm and ±1.0 mr in x_0 and θ_0, respectively. For ±1.0 mm accuracy in the vertical plane, errors of ±1.5 mm and ±2.9 mr are found for y_0 and ϕ_0. On the other hand the positioning of the back wire chambers is a compromise between resolution and loss of pions to decay.

The multwire proportional counters were constructed at the Carleton University Workshop [23]. The front two chambers before the dipole have dimensions 150 mm × 150 mm and the two large chambers after the dipole have length 600 mm and height of 300 mm. The anode plane has a vertical wire spacing of 2 mm while the cathode planes have a horizontal spacing of 1 mm. The wires are soldered to a delay-line strip with 0.55 ns between individual wires and an amplifier located at each end of the strip. The large horizontal extent of the back chambers required that three 200 mm delay lines be used. The gas mixture used in these chambers is typically 69.7% argon, 30% isobutane and 0.3% freon at standard temperature and pressure.

The effects of multiple scattering in the spectrometer are significant. Presently 12.5 μm (0.0005 in.) mylar windows are on the two front wire chambers and 50 μm (0.002 in.) mylar windows are on the large back chambers. This alone limits the resolution to 0.27% in $\Delta p/p$ or 250 keV at 50 MeV (see fig. 3). The addition of 1 atm of an argon-isobutane gas mixture into the wire chambers degrades the resolution to 0.55% or 480 keV. Replacing the argon-isobutane gas mixture with a methane gas mixture is calculated to yield a resolution of 0.35% in $\Delta p/p$ or 300 keV. In the latest experiments 1 atm He gas was circulated through the vacuum box to give a total spectrometer resolution of $\Delta p/p = 0.9\%$ or 770 keV at 50 MeV.

A spectrometer trigger is defined by a logic AND of signals from all three scintillators (E1, E2, E3) (see fig. 1). The first two scintillators E1 and E2 are 1 m long and 6.4 mm (1/4 in.) thick with a single phototube at either end. A third scintillator E3 is also 1 m long but 12.7 mm (1/2 in.) thick and has four phototubes. A true event has a coincidence of these three plus the in-beam BM1 scintillator, which is a 0.8 mm (1/32 in.) thick detector mounted before the scattering chamber.

The pion flux is monitored by several techniques. The two plastic scintillators BM1 and BM2 measure the absolute number of particles passing through the target. A second beam monitor is a muon telescope [24] consisting of two small 10 mm × 10 mm scintillators separated by 300 mm and is set at an angle of approximately half of the maximum laboratory angle to measure the muons from pion ($\pi \to \mu\nu$) decay. The beam intensity was also measured by a 'rate reduction monitor' (RRM): a detector constructed with 10 mm circular pieces of NE102 scintillator mounted in a piece of plexiglass giving an overall efficiency of ~10%. The RRM and muon telescope monitor any inefficiency in the primary beam monitors at high incident pion flux. All three monitors were checked for reliability for fluxes ranging from 5×10^4 to 4×10^6 pions per second and all were found to be consistent at the 97% confidence level.

5. Experimental results

The QQD spectrometer was assembled and set up for the first time in the summer of 1982, about fifteen months after the conceptual design. Since then both tuning of the system and experiments have led to several improvements.

The transfer coefficients to each wire chamber were measured by scattering a pion beam off a mask of nickel-chromium wire 3 mm wide × 0.5 mm thick spaced every 3 mm in both the horizontal and vertical planes. Coefficients were then calculated using a linear least squares fitting routine. The values for the back wire chambers (WC4 and WC5) are shown in table 2 and compare favourably to the TRANSPORT prediction. With these coefficients a combined channel-spectrometer resolution of $\Delta p/p = 1.3\%$ or 1.1 MeV at 50 MeV is presently obtained. The momentum bite of the M13 channel was limited to $\Delta p/p = 0.5\%$ corresponding to 450 keV; however, this increased to 700 keV when the full geometric acceptance of the channel was used. A typical spectrum from the scattering of π^- from CH_2 target at 130° and 50 MeV is shown in fig. 4.

The acceptance of the spectrometer was measured by elastically scattering pions off a CH_2 target at a fixed angle and varying the spectrometer fields. Fig. 5 shows that the acceptance is flat from -10% to 10% in $\Delta p/p$ for a beam spot of ±20 mm in both planes. The solid angle predicted by REVMOC, for a similar beam spot used during the experiments, agrees quite well with the measured data. The absolute solid angle was determined by measuring the yield of pions scattered from the hydrogen in the CH_2 at various angles and normalizing to the π^+p differential cross section of the phase-shift calculation of Arndt et al. [25], which is based on fits to the low energy scattering experiments of Bertin et al. [26] and Frank et al. [27]. The solid angle was found to be 18±1 msr for a beam spot of approximately ±20 mm radial and ±20 mm axial extent.

The muon and electron contamination of the incident pion beam can be easily separated by time-of-flight measurements with a scintillator in the pion beam against the cyclotron rf. At 128.3 MeV/c (50 MeV pions) the $\pi:\mu:e$ ratio is 1000:58:8 for π^+ and 1000:44:43 for π^-. Typical time-of-flight spectra are shown in fig. 6.

Muons that appear in the spectrometer from decayed scattered pions are removed by eliminating particles whose paths cannot be fitted by the ray-tracing routine. Although over 30% of the pions decay in the 2.28 m path, Monte Carlo estimates indicate that typically less than 2% of the events accepted as pions were actually muons.

6. Conclusions

Since its completion the QQD spectrometer has been used to study nuclear matter distributions in nuclei with elastic pion scattering

[13,28], and inelastic scattering experiments [29]. Future experiments include more inelastic scattering, double charge exchange and coincidence experiments. However, before some of these experiments can be initiated, improvements to the channel and the spectrometer are necessary. Short-term improvements include removing the helium gas from the spectrometer vacuum vessel and operating the wire chambers at lower pressures (~0.5 atm) with thinner reinforced mylar windows. Active coils are planned to be installed into the M13 dipoles B1 and B2 in order to remove the higher-order geometric aberrations. This will allow the use of the full momentum acceptance of the channel in a dispersive mode. Longer-term improvements include the installation of a 200 μm thick Si strip counter with 0.1 mm position resolution into the second focus F2 of M13. This will allow the use of the full momentum acceptance in an achromatic mode. This is important in experiments that use small exotic targets. Further gains in spectrometer resolution will require the replacement of the present multiwire proportional counters with low pressure (~1/10 atm) drift chambers that can operate at high pion fluxes.

The authors would like to thank D. Clark, A. Otter and J. McIlroy and their groups at TRIUMF for their assistance in the design and construction of the QQD spectrometer. We are grateful for the loan of a quadrupole magnet and dipole magnet by Kernforschunsanlage, Jülich.

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Table 1

Specifications of M13 pion channel and QQD spectrometer.

	M13 channel	QQD spectrometer
Solid angle	38 msr	18 msr
Momentum acceptance	±4%	±20%
Momentum resolution	0.5% for 10 mm production target	$p/\Delta p = 1000$
Momentum range	20-135 MeV/c	<150 MeV/c
Focal plane:		
Dispersion		-1.06 cm/%
Radial magnification		-0.54
Tilt angle		72°
Path length	9.4 m	2.28 m
Intermediate F2 focus:		
Dispersion	+1.26	
Radial magnification	-0.9	
Focal plane tilt angle	1°	
Angular range		30-135°

Table 2

Comparison of experimentally measured coefficients to TRANSPORT prediction

	Wire chamber 4		Wire chamber 5	
	TRANSPORT	Experimental	TRANSPORT	Experimental
R_{11}	1.25	1.28 ± 0.05	0.35	0.22 ± 0.03
R_{12}	0.128 cm/mr	0.122 ± 0.005	0.061	0.051 ± 0.003
R_{16}	-0.610 cm/%	-0.61 ± 0.02	-0.912	-0.91 ± 0.03
T_{111}	-8.6×10^{-2}/cm	$-10 \pm 2 \times 10^{-2}$	-1.3×10^{-1}	$-1.5 \pm .3 \times 10^{-1}$
T_{112}	-1.5×10^{-2}/mr	$-1.5 \pm .5 \times 10^{-2}$	-2.2×10^{-2}	$-2.5 \pm .5 \times 10^{-2}$
T_{122}	-6.3×10^{-4} cm/mr^2	$-8.0 \pm .5 \times 10^{-4}$	-9.5×10^{-4}	$-12 \pm 1 \times 10^{-4}$
T_{116}	$+3.3 \times 10^{-2}$/%	$5 \pm 2 \times 10^{-2}$	6.2×10^{-2}	$6.6 \pm .5 \times 10^{-2}$
T_{126}	3.3×10^{-3} cm/mr-%	$8 \pm 3 \times 10^{-3}$	5.6×10^{-3}	$8.5 \pm 1.0 \times 10^{-3}$
T_{166}	4.1×10^{-3} cm/%^{2}	$5 \pm 2 \times 10^{-3}$	6.1×10^{-3}	$11 \pm 3 \times 10^{-3}$

Figure captions

1. Schematic layout of the TRIUMF M13 pion channel and spectrometer. The symbols denote: BL1A is the primary beam line and T1 is the pion production target; Q1-Q7, SX1-SX2 and B1-B2 are the channel quadrupole, sextupole and dipole magnets, respectively; F1 and F2 are the intermediate focus points; QT1-QT2 and BT are the spectrometer quadrupole and dipole magnets, respectively. The in-beam scintillation counters are BM1, BM2 and RRM and spectrometer scintillation counters are labelled E1, E2 and E3.
2. Schematic view of the spectrometer in the dispersive plane. The symbols WC1-WC5 are locations in which wire chambers are positioned; (note WC2 is usually empty). The solid line represents the central momentum trajectory while the dashed lines are for ±20% $\Delta p/p$ trajectories.
3. Effects on resolution of various gases (at STP) inside the spectrometer. The calculation includes the windows on the wire chambers for all three cases. The lower curve labelled VACUUM is calculated for no gases at all in the spectrometer, while the two upper curves include the wire chamber gases as well as 1 atm of helium or air inside the spectrometer vacuum chamber.
4. Raw spectrum of π^- of $p = 128$ MeV/c scattered from a CH_2 target of 0.335 mg/cm^2 at a laboratory angle of 129.5°. The lowest excited states in ^{12}C are indicated with their excitation energy, spin and parity.
5. Relative acceptance of the spectrometer as a function of momentum. The solid line is a REVMOC ray-trace calculation. The data was taken by scattering pions from CH_2 at a fixed laboratory angle and varying the spectrometer magnetic fields.

6. Time-of-flight spectra measured in the pion channel at 128 MeV/c. The particles were detected with a scintillator BM1 in front of the scattering target which is approximately 9.8 m from the pion production target. The cyclotron rf signal served as the stop signal.

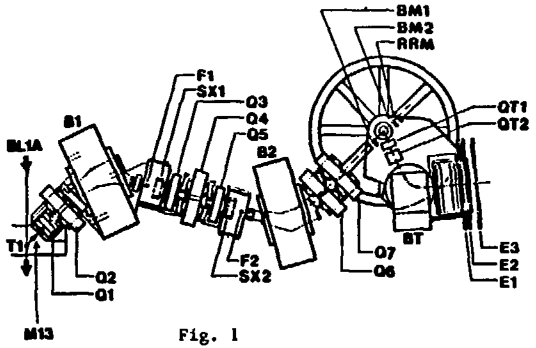

Fig. 1

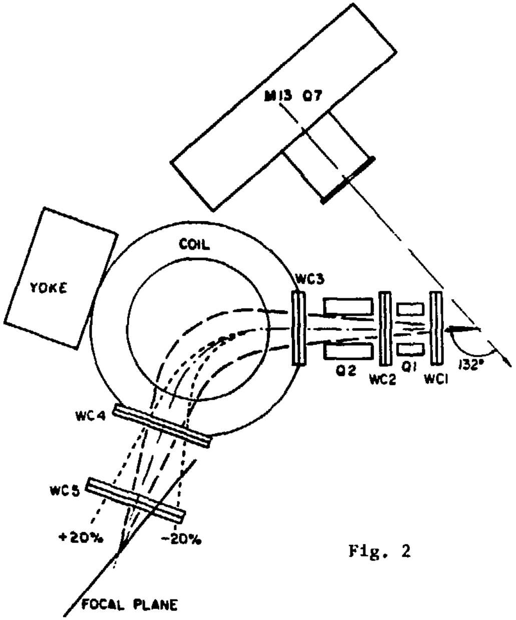

Fig. 2

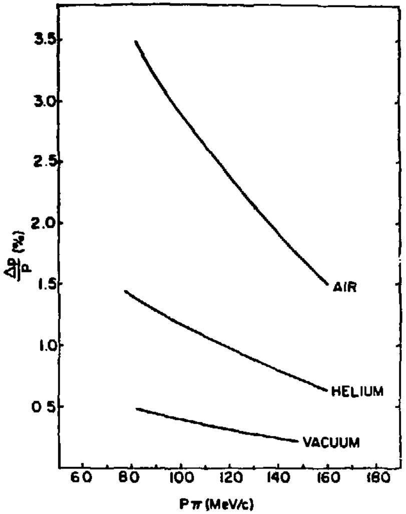

Fig. 3

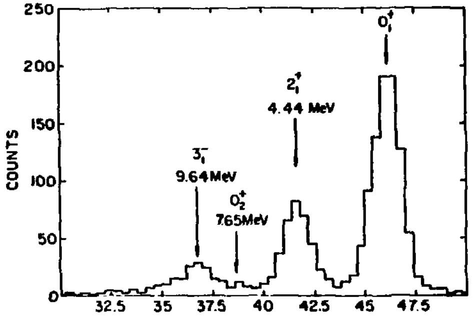

Fig. 4

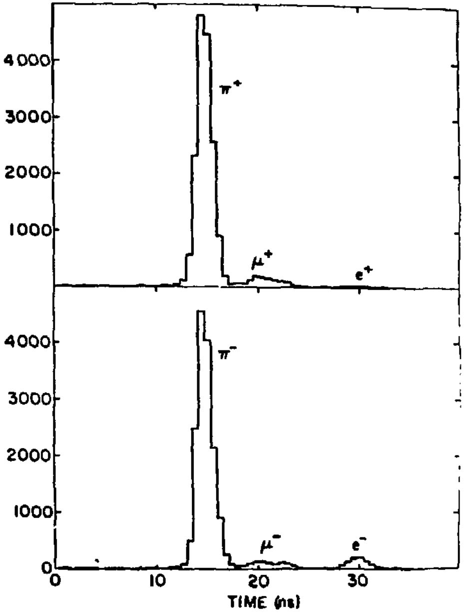

Fig. 5

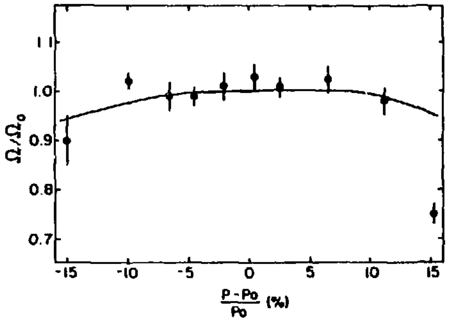

Fig. 6