Session B7: Charm Search and Related Topics

Chairman: R. HOFSTADTER

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B 7 Search for Short-Lived Particles in Nuclear Emulsion Exposed to Accelerator Beams without External Detectors

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Because of high spatial resolving power, nuclear emulsion is, at present, the only technique by which we can directly observe the decay of a short-lived particle with life time of $10^{-12\sim14}$ sec. The first evidence of such a particle was obtained by a Japanese group[1] in 1971, in super high energy interactions due to cosmic rays. Mass and life time of the particle was estimated as $1.5\sim3.5$ GeV and $0.2\sim0.4\cdot10^{-13}$ sec. Just after the discovery, that particle was pointed out to be possibly a charmed particle by a Japanese theoretical group.[2] Following the pioneering work, much effort has been concentrated on the emulsion experiment at accelerator energies to observe decays of such particles. To this conference, three papers are contributed reporting results of search for short-lived particles in nuclear emulsions exposed to beams without external detectors. Table I shows the summary of experimental conditions and results of these new contributions and some other works.

Bannik *et al.*[3] analysed 24,000 interactions induced by 60 GeV/*c* negative pions and 70 GeV/*c* protons. They focussed their attention to the presence of a high energy electron among the decay products of candidates of new particles observed within 100 μm from the primary vertex. Electrons are identified by the multiple scattering, the rapid loss of energy and also the relation of ionization with momentum. They got one charged chandidate from 10,000 negative pion interactions and one charged and two neutral ones from 14,000 proton interactions. The background level for this type of event is very small and equal to 10^{-3} for all 24,000 analysed events. They estimated the production cross-section for semileptonically decaying charmed particles to be 5 μb.

Chernyavsky *et al.*[4] analysed 1,120 proton interactions of 400 GeV/*c*. They searched decays of charmed particles in forward cone and up to 1 mm from the interaction vertex. Picking up particle groups with opening angle even smaller than 3 degrees, they found a sample of 21 events which is a mixture of electron pairs and white stars. After subtracting electron pairs, they claimed that they have got 9 candidates. All of them took place within 100 μm from the primary stars. From the slope of integral curve in Fig. 1, they got a mean life time as $2\cdot10^{-14}$ sec. As for the production cross-section, they derived a value of 120 μb assuming a linear *A*-dependence of charm production. In their analysis, however, effect of detection bias of electron pairs was not considered, and those quoted values should be considered as preliminary ones as stated by the authors.

Ushida *et al.*[5] also analysed 312 interactions produced by protons of 400 GeV/*c*. They found the first event in which a pair of neutral short-lived particles were observed. Detectors they utilized are not pure emulsion stack but so called emulsion chambers. The emulsion chamber is a complex detector which consists of more than hundred layers of two fold emulsion counters coated on both surface of thin plastic plate or film, and thin lead or

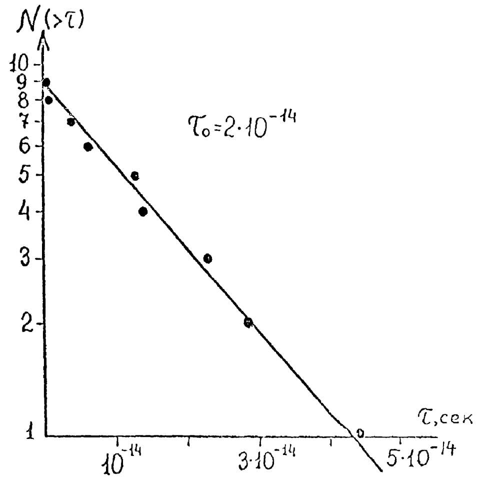

Fig. 1. Integral distribution of the charmed particles relative time passed in their rest frame up to the moment of decay. No. 308: Chernyavsky *et al.*

Table I.

	Beam	Searched		Detecting angle	Candidate		Cross-section
		events	area (mm^2)		charged	neutral	(μb)
Pellicle stacks							
P.L. **65B**, 480, (1976) Coremans-Bertrand	300 GeV/c p	62302	0.15×0.15 +2 mm	3°	(10)	(13)	<1.5 (90%)
L.N.C. **19**, 32, (1977) Bozzoli	300 GeV/c p 400 GeV/c p	8701 7997	0.3×0.6 +2 mm	3°	(8) (16)	(8) (5)	<7 (90%)
#154 Bannik	60 GeV/c π^- 70 GeV/c p	10000 14000	0.1×0.1		1 1	0 2	5 (semi-leptonic)
#308 Chernyavsky	400 GeV/c p	1120	0.06×1.0	0.05°	2	7	120
Emulsion chambers							
P.T.P. **53**, 1859, (1975) Hoshino	205 GeV/c p	365	0.3×0.5	10^{-3} rad	1	1	20∼200
N.C. (submitted) Fuchi	400 GeV/c p	1008	0.5×2.0 0.5×5.0	10^{-3} rad	2	0	8∼70
#492 Ushida	400 GeV/c p	312	0.3×5.0	10^{-3} rad	0	one pair	*·10

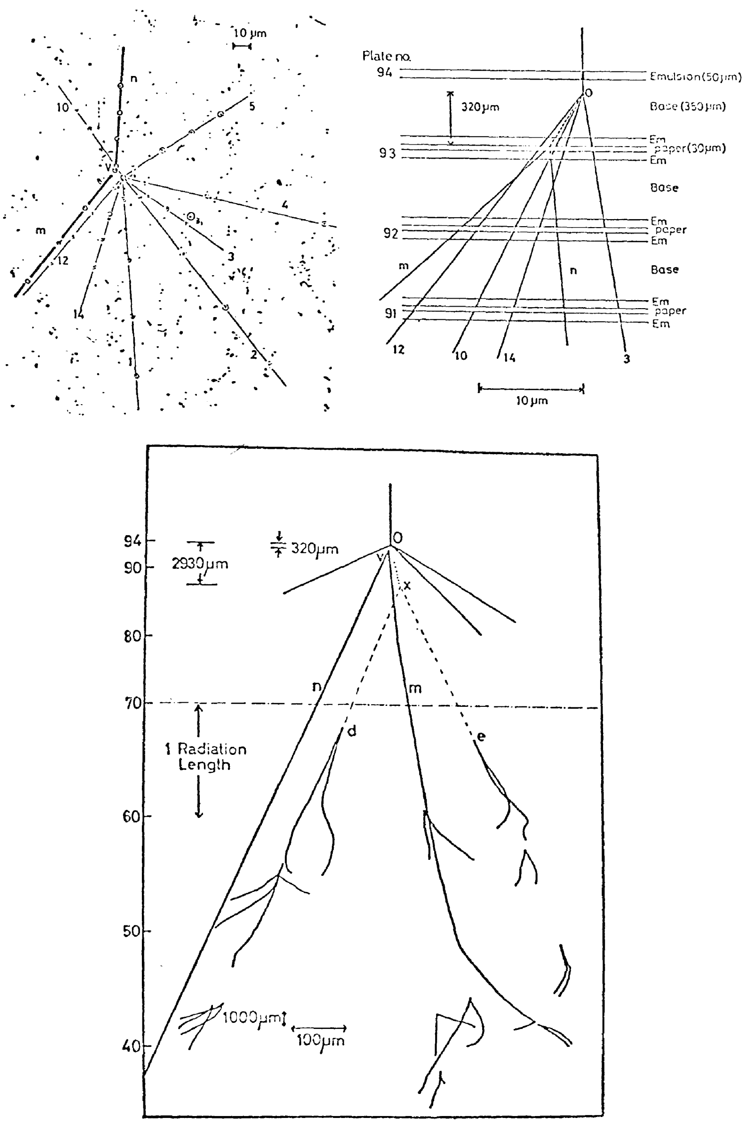

Fig. 2. No. 492: Ushida *et al.*

tungsten plates to form a target part and an analysing part. Electrons are clearly discriminated from other charged particles by inspecting cascade showers induced by them in the analysing part. In the observed event, a vee is observed originating at 320 μm down stream from the interaction point, as is shown in Fig. 2. One of tertiary m was identified as an electron (positron), because of a cascade shower it induced in the analysing part. The other tertiary n was identified as a hadron, because of a nuclear interaction it produced. No coplanarity condition is satisfied among neutral line and two charged legs of the vee. These features are suggestive, to the authors, of a semileptonic decay of a short-lived neutral hadron. Beside that, flight lines of two γ rays traced back from each first pair were assertained to intersect at the point 2930 μm down stream from the original interaction. Invariant mass of these two γ rays was consistent with that of the neutral pion. No other particle in vicinity or no other γ ray in down stream of the point was observed. These are suggestive of a decay of another short-lived neutral particles into a neutral pion and other neutral particle(s). These informations lead them to conclude that this is a pair creation and decay of neutral charmed particles in a same event. Table II gives a summary on these two particles. The mass of the V^0 is consistent with that of a charmed meson D^0.

Table II. Summary of a pair of short-lived neutral particles in EM–25.

	V^0	X^0
Decay	e+had+?	π^0+?+?
Flight length (μm)	320±20	2930±200
Visible energy (GeV)	$E_{had}=52^{+8}_{-6}$ $E_e=6.25^{+2.4}_{-1.4}$	$E_{\gamma 1}=11.1\pm 3$ $E_{\gamma 2}=2.9\pm 0.9$
Mass (GeV)	1.6∼2.0 (eKν)	0.9∼1.5 (Two body) ∼2.0 (Three body)
τ (sec)	$\sim 3.5\times 10^{-14}$	$<1.4\times 10^{-12}$

Table III gives a summary of the results on the mass, the life time and the cross-section of short-lived particles reported in the three contributing papers. Without external detectors, it is difficult to identify all tertiary particles, but estimated masses are not inconsistent with that of charmed meson or baryons. As for the life time, two papers in which only unassociated candidates were observed gave values of order of 10^{-14} sec, while Ushida *et al.* who observed an associated pair estimated it as $5\sim 7\cdot 10^{-13}$ sec, taking into account of their former results.[6] There may be different life times for various charmed mesons and baryons, neutral and charged ones, but the problem of life time should be settled after observing a good number of pairs of charmed particle candidate. About the production cross-section of charmed particles, a value of several tens to a hundred μb seems to be a possible common conclusion of the three papers considering that the first group confined themselves only within semi-leptonic channel. This is

Table III.

Paper No: Authers beams	Observed candidate	Mass (GeV)	Lifetime (sec)	Cross-section (μb)	Comment
154: Bannik *et al.*					
60 GeV/*c* π^- 70 GeV/*c* p	charged 1 charged 1 neutral 2	1∼3	$10^{-14}\sim 10^{-13}$	∼5 (semi-leptonic)	partners are not found
308: Chernyavsky *et al.*					
400 GeV/*c* p	charged 2 neutral 7	(charmed baryon)	2.0×10^{-14}	∼120	partners are not found
492: Ushida *et al.*					
400 GeV/*c* p	neutral 2	1.6∼2.0 (Keν) ∼2.0 (π^0 ??)	3.5×10^{-14} $<1.4\times 10^{-12}$	several tens	one pair is observed

not inconsistent with the results of the beam dump experiments at CERN.[7] This is also not inconsistent with preceding emulsion experiments[8] provided that the life time of charmed particles is in between $5\sim7\cdot10^{-13}$ sec, where their detection efficiency of a pair of such particles is as low as 10%.

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B 7 Search for Short-Lived Particles in Nuclear Emulsion Exposed to Accelerator Beams: A Short Review of Neutrino Experiments with External Detectors

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It is by now well established that neutrino interactions constitute a copious source of charmed particles, the lifetime of which being expected to lie in the range 10^{-12} to 10^{-14} s.* Direct observation of the production and subsequent decay of such short-lived particles is only possible at present in photographic emulsion with its high spatial resolution.

This report presents a short survey of different searches for these particles already performed or to be carried out soon in high energy neutrino beams and using photographic emulsion in conjunction with external detectors. The external detectors are used (i) to help in locating the neutrino interactions in the emulsion and (ii) to provide maximum information on the secondaries (identification and momentum).

§1. FNAL E247 Experiment[2,3]

Seventeen litres of emulsion have been exposed early in 1976 to the wide-band neutrino beam at Fermilab. Tracks of charged secondaries from neutrino interactions in the emulsion were observed in a wide-gap spark chamber with two 15 cm gaps and a sensitive area of 100×80 cm² followed downbeam by a system of four narrow-gap chambers separated by scintillaction counters and lead plates forming a shower detector. The experimental arrangement was completed by a rudimentary muon identifier allowing the detection of forward muons of momentum greater than 2 GeV/c.

Vertex reconstruction was based on the measurements of the tracks in the wide-gap chamber; the system of narrow-gap chambers has proven useful by providing a crude selection of events containing particles of momentum greater than $\sim$500 MeV/c, more suitable for vertex reconstruction.* The measurements

* Recent bubble chamber studies[1] have set an upper limit of $\sim10^{-12}$ s (90% CL) to the lifetime of charmed particles.

* The set-up does not contain a magnet.

of events with more than 2 prongs converging to a point inside the emulsion have yielded 194 vertex predictions. The estimated number of neutrino interactions (both charged and neutral current events) in the emulsion was 230±70, from data obtained in the 15′ bubble chamber running 50 m downstream in the same beam. Only 37 neutrino interactions were found in the emulsion after the scan of an area of 328 cm² (pellicle thickness is 600 μm). An additional area of 5360 cm² was scanned fruitlessly for the remaining 157 predictions.

The reasons for the low success rate for locating neutrino interactions in the emulsion have been carefully investigated. A summary of the major loss factors affecting the experiment is given in their contribution to the Conference. Decays of unstable particles after a distance of a few microns (flight time around 10^{-14} s) should have been seen. Only one likely example of a charmed particle has been detected which decayed after a range of 182 μm (flight time $\sim 6\times10^{-13}$ s) into three charged particles and possibly a V^0 particle observed in the spark chamber system.[2] The chance of this event being a background nuclear interaction of a non-charmed hadron was estimated to be 1 in 400.[3]

A fruitless systematic search for neutral short-lived particles was made over 2 mm downbeam from the 37 neutrino interactions and within a cone of semi-vertical angle of 30°.

In an attempt to extend the search for short-lived particles down to lifetimes around 10^{-15} s a method used previously in the determination of the π^0 meson lifetime has been applied to a sample of 28 events.[4] Using a Koritska R4 microscope with digitized micrometric eyepieces the coordinates of a series of individual grains on each track of minimum ionization were measured (in the plane of the emulsion pellicle only). These measurements were fitted to straight lines by a least squares procedure and the projected distance Δ of each line to the event vertex was determined. The results are illustrated in Fig. 1 giving a scatter plot of Δ *vs* $\Delta/\delta\Delta$. The maximum value of Δ is 0.37 μm and in no case is the value of $\Delta/\delta\Delta$ greater than 3. The distribution of the values of $\Delta/\delta\Delta$ is compatible with a gaussian (0, 1). From these preliminary results there is no evidence for decays of particles with lifetime around 10^{-15} s.

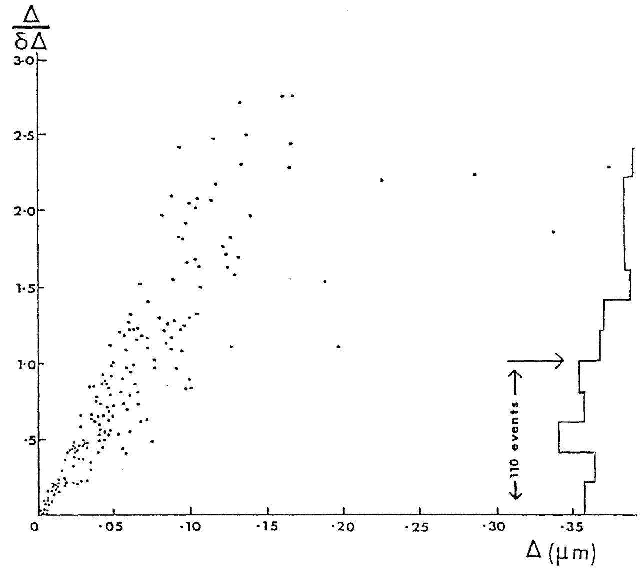

Fig. 1. *E247 experiment*: Scatter plot of Δ *vs* $\Delta/\delta\Delta$; Δ is the distance of closest approach to vertex for all tracks of minimum ionization from 28 events.

§2. CERN WA17 Experiment[5]

The experimental set-up is shown schematically in Fig. 2. The emulsion stacks, covering a cross sectional area of ~ 0.25 m², are located in front of the beam window of BEBC filled with liquid H_2 and operated in a 35 kG magnetic field. Two multiwire proportional chambers *U* and *D* are used to correlate the BEBC and emulsion reference systems. Chamber *D*, covering the whole emulsionstack area, can also be used as an help in the vertex reconstruction. A veto coincidence counter system VCS linked to the BEBC EMI can be used as event trigger ($\overline{\text{V}}$CD) and to select the the relevant EMI time slot.

A total volume of 30 *l* of emulsion has been exposed in the **z** wide-band beam at the SPS during two runs corresponding to $\sim 10^{18}$ protons on the target and yielding 206,000 BEBC pictures. The expected number of charged current neutrino interactions (CC) in the emulsion is between 850 and 1000.

Up to now 84,000 pictures have been scanned (partly using the electronic information from VCS) for events with more than 2 prongs apparently converging to a point inside the emulsion. The measurements of these events have yielded 260 predicted vertices in the emulsion, of which 154 contain a muon candidate. The corresponding expected num-

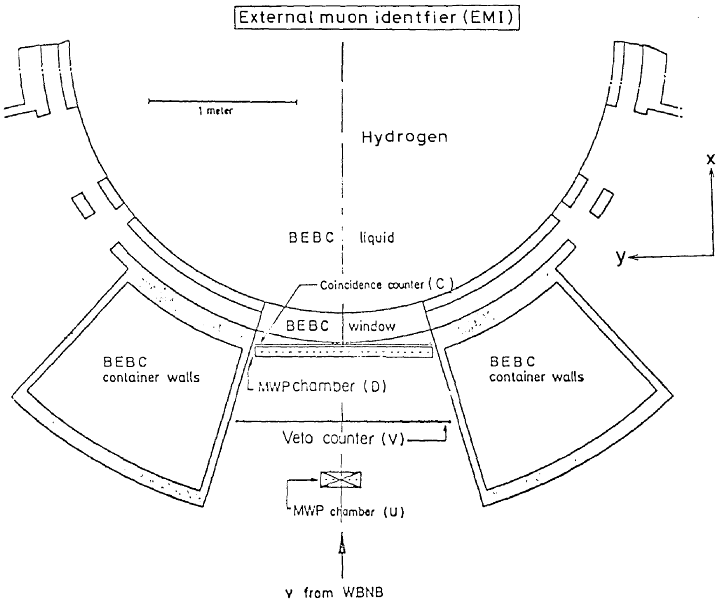

Fig. 2. Schematic set-up of the CERN WA17 experiment.

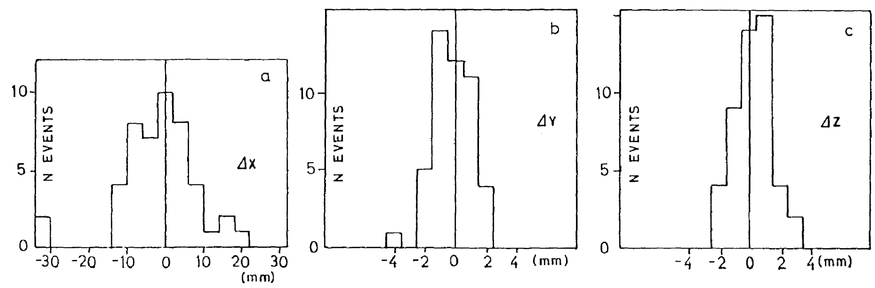

Fig. 3. *WA17 experiment*: 3a, b, c. Distributions of the differences between the observed and predicted vertex positions (Δz along the beam, Δx and Δy across the beam).

ber of CC events is ~ 300 indicating a 50% selection efficiency due partly to the loss of low multiplicity events resulting from the geometry of the set-up, the scanning criteria and the influence of the strong BEBC magnetic field.

Of these predictions, 112 (68 CC) have been searched for in emulsion and 50 (31 CC) have been found. Part of the loss is accounted for by the known emulsion scanning inefficiencies. In addition, secondary interactions occurring in the emulsion and/or the BEBC window can contribute by leading to wrong vertex predictions. The significantly higher success rate of this experiment compared to the FNAL E247 experiment is largely explained by the much more complete information provided by BEBC allowing a better selection of the events.

For the found events, the distributions of the differences between the observed and predicted vertex positions are given in Fig. 3a, b, c. These distributions characterized by rms dispersions $\sigma_x = 1.1$ mm, $\sigma_y = 1.3$ mm and $\sigma_z =$ 9 mm are almost identical to those observed in the E247 FNAL experiment.[3]

All relativistic particles of the found events have been followed over a distance of at least 5 mm, unless they interacted or left the emulsion before. No example for the decay of short-lived particles has been found. Combinding these data with the results of the E247 experiment increases the probability of the E247 event to be background to $\sim 1/170$. The scanning for neutral decays (same procedure as in E247) is in progress.

Extrapolating from the present results it is expected that this experiment, when completed, will provide about 200 charged-current events in the emulsion.

§3. The Serpukhov Experiment[6]

An hybrid system made of 8 stacks of emulsion (16 *l*), three-electrode spark chambers of gap widths 2.4 cm and scintillation counters has been exposed in June 1976 to the Serpukhov neutrino wide-band beam. This system was located in front of the ITEP neutrino detector consisting of a hadron calorimeter made of spark chambers sandwiched with Al foils, followed by a magnetized iron muon spectrometer.

The exposure corresponded to $\sim 4\times 10^{17}$ protons of 70 GeV on the target, which would lead to about 60 charged current neutrino interactions in the emulsion. From the analysis of the events with more than 2 prongs in the three-electrode spark chambers, 20 vertices were reconstructed in the emulsion. Eight of the predicted events were found. No evidence for charged or neutral short-lived particle decaying within 1 mm from the neutrino interaction vertices was found.

A new run with 30 *l* of emulsion is now being analyzed.

§4. A Gargamelle Test Run

A test exposure has recently been performed at CERN in which 2.4 *l* of emulsion were located *inside* Gargamelle filled with a mixture of propane and heavy freon operating at ~ 30 atmospheres and ~ 60°C. The stack was located in an aluminium box accurately mounted in a pressure vessel made of aluminium alloy (thickness of 2.4 cm), maintained at atmosphere pressure and attached to the front door of Gargamelle. The box as thermally insulated from the pressure vessel by polystyrene foam; it contained channels through which cold freon as circulated so that the temperature in the box was kept below 15°C.

Respectively 65,000 and 80,000 pictures were taken in the $\bar{\nu}$ and ν wide-band beams available at the SPS, corresponding to $\sim 3\times 10^{17}$ and $\sim 5\times 10^{17}$ protons on the target. All the ν pictures and 40% of the $\bar{\nu}$ pictures have been scanned yielding about 130 candidates of neutrino interactions in the emulsion.*

The introduction of the vessel had no serious distrurbing effect on the quality of the Gargamelle pictures.

§5. Planned Experiments at FNAL

Three emulsion experiments are expected to run at Fermilab in fall of this year:

(i) *Neutrino 564* (Fermilab–IHEP–ITEP–Krakow–JINR–Kansas–Washington Collaboration).

Two sealed boxes containing a total volume of 22 *l* of cryogenically sensitized emulsion will be located inside the 15′ bubble chamber filled with deuterium, one above and one below the nosecone of the chamber.

Parasitically with the bubble chamber neutrino research programme the experiment aims for a wide-band beam exposure with 3×10^{18} protons on target providing about 1000 neutrino interactions in the emulsion.

(ii) *Neutrino 531* (Aichi–Fermilab–Kobe–McGill–Nagoya–Ohio State–Osaka–Ottawa–Toronto Collaboration).

A total volume of 26 *l* of emulsion will be placed in front of a spectrometer consisting of two sets of drift chamber planes separated by a magnet allowing precise track reconstruction, momentum determination and particle identification ($\pi^{\pm}$, $K^{\pm}$, $e^{\pm}$, π^0).

An exposure in the wide-band beam corresponding to 3×10^{18} protons on target has been requested.

(iii) *Neutrino 553* (Cornell–Krakow–Lund–Pittsburg and Toronto Collaboration).

A 15 *l* emulsion target made of 32 modules is placed in front of a 8 kG magnet followed by spark chambers and an electromagnetic and hadronic shower detector (lead and iron segmented detector in combination with 56 flashtubes). Each target module consists of emulsion pellicles (area 2×8.5 cm^2) and 6 gold-plate self-marking spark chambers. The location of the events in the emulsion is achieved by finding tracks in detectors of gradually increasing spatial resolution. The expected size of the emulsion volume to be scanned for each event is ~ 0.1 mm^3!

In conclusion, it can be expected that within the next year the above running and planned experiments will provide about one thousand neutrino interactions in emulsion, a sample large enough to settle the question of the lifetime of charmed particles.

Acknowledgements

My thanks are due to E. H. S. Burhop, N. Dzelepov, L. Hand, A. Montwill, I. Ot-

* The expected numbers of events in the emulsion are respectively $\lesssim 10$ and ~ 60 in the ν and $\bar{\nu}$ exposures.

terlund, N. W. Reay and L. Voyvodic who kindly supplied me information for preparing this report.

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B 7 Prompt Neutrino Production in Proton Nucleus Collisions

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Production of prompt neutrinos in proton-nucleus collisions has been studied at CERN, BNL and Serpukhov. Neutrino detectors were exposed to particles produced in 400 GeV, 28 GeV, and 70 GeV proton beam dumps, respectively. The three experiments at CERN (BEBC, Gargamelle and CDHS) observe an excess of single electron events or of muonless events and they conclude that these are due to prompt electron neutrinos produced in the beam dump. If this prompt neutrino flux is interpreted as due to charm production and semileptonic decay, the cross-sections $\sigma(pp\to D\bar{D}+X)$ are estimated to be 100–200 μb (BEBC, GGM) or 40 μb (CDHS). An $A^{2/3}$ dependence, $\Gamma(D\to Ke\nu, K^*e\nu)/\Gamma(D\to all)=0.1$ and a range of productin models are assumed. The experiments at BNL and Serpukhov give upper limits to this cross-section compatible with the observed numbers.

All experiments have searched for axion production, and the upper limits for this process make improbable the existence of such a particle with the properties proposed.

§1. Principle of Beam Dump Experiments

The aim of these beam dump experiments is to search for new short-lived ($\lesssim 10^{-11}$ sec) particles which through their leptonic decays would create neutrinos penetrating the shielding and interacting in the neutrino detectors.[12]

In order to suppress conventional sources of neutrinos, the proton beam was dumped into a dense, extended Cu target such that π and K mesons and Λ and Σ hyperons have a high probability of interacting before they can decay (Fig. 1). The decay rate is reduced by the ratio of the nuclear interaction length over the length of the decay region, 0.15 m/350 m $\propto$ 1/2000. Neutrinos produced at zero degrees were then detected in three detectors, the BEBC (72% Ne, H_2)[1] and Gargamelle (Freon)[2] bubble chambers and the magnitized Fe-scintillator-calorimeter of the CDHS group.[3] These heavy liquid bubble chambers are particularly suited for the detection of electrons, while the CDHS experiment is well suited for (multi) muon detection and can distinguish electron showers from hadronic showers on a statistical basis.

The experiments done subsequently at lower energies use different methods for the investigation of a prompt neutrino signal: the IHEP–ITEP group[4] at Serpukhov varies the

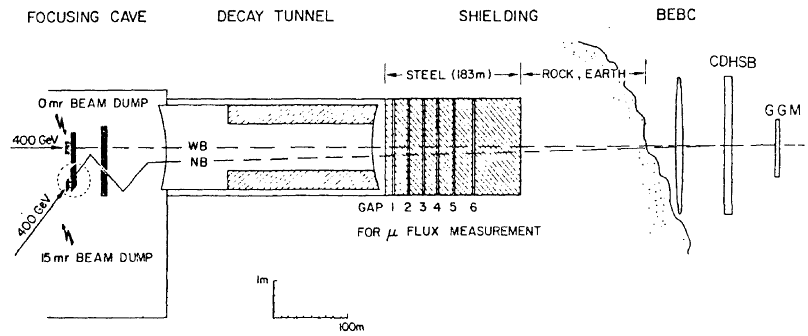

Fig. 1. Geometry of beam-dump experiments at CERN

Table I. Detectors.

	BEBC	CDHS	GGM	BHP	ITEP/IHEP
Material	72% Ne H_2	Fe-Sci	Freon	Sci. liq.	Al
Fid. mass	13 t	580 t	10.5 t	11 t	10 t
e^- identification	$(90\pm5)\%$	indirect	very good	—	—
solid angle Fid. length [m]	10 μsr 3	10.8 μsr 9.3	1.8 μsr 4.6	0.4 msr 3	0.5 msr 6
Proton energy Int. protons	400 GeV 3.5×10^{17}	400 GeV 4×10^{17}	400 GeV 3.5×10^{17}	28 GeV 49×10^{17}	70 GeV 7.4×10^{17}
Method of search	Excess electron ev.	Excess NC events	Excess electron ev.	Comparison Beam dump/ 15 cm target	Density variation

density of the beam dump in order to extrapolate to infinite density, and the BNL–Harvard–Pennsylvania (BHP) group[5] at Brookhaven compares the rate of neutrino-induced events from a beam dump with the one obtained from a 15 cm target, thus subtracting the neutrino production by π and K mesons experimentally.

Table I lists some of the properties of the experiments reported to the conference.

§2. Observations in Beam Dump Experiments

a) BEBC (ABCLOS Collaboration)

Of the 70 events with $E_{vis}>10$ GeV, there were 29 with a μ^-, 11 with an e^-, 5 with μ^+, 4 with e^+ and 21 without identified lepton (NC). The high rate of electron events is not expected on the basis of conventional sources. Taking the μ^- and μ^+ samples as reference, the number of e^- events due to electron neutrinos from π and K decays is calculated to be 1.8 ± 0.4 (observed 11) and the expected number of e^+ events 0.5 ± 0.25 (observed 4). Similarly, in the narrow-band beam run, where the proton beam hits the target at an angle of 15.6 mrad relative to the neutrino beam line, corresponding to a "skew beam dump experiment", there are 12 μ^- events and 8 e^- events compared to an expected number of 1.3 ± 0.4. The visible energies of the μ^- and e^- events are shown in Fig. 2.

b) Gargamelle

Also in this chamber, an excess of electron events is observed. From 16 events with a μ^+ or μ^-, one expects 1.1 ± 0.3 electron events, while 9 are observed. Visible energies of these events are shown in Fig. 3.

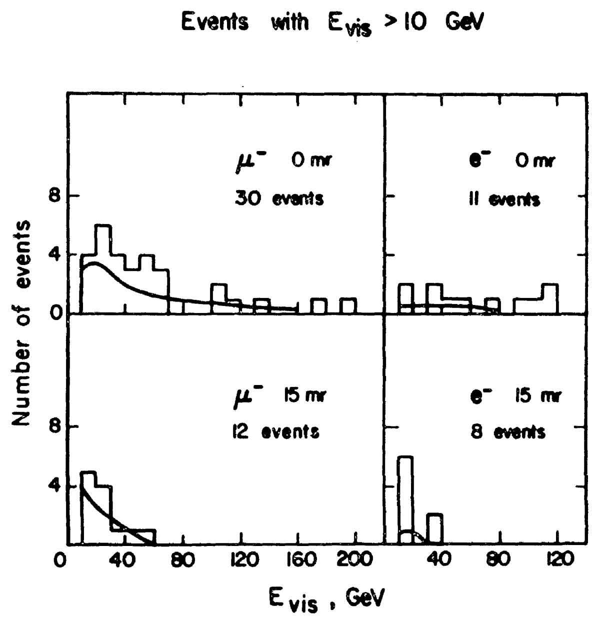

Fig. 2. Visible energy of μ^- and e^- events in BEBC.

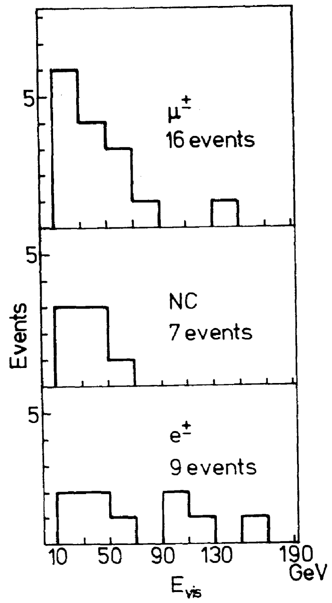

Fig. 3. Visible energy of μ^-, e^- and NC events in GGM.

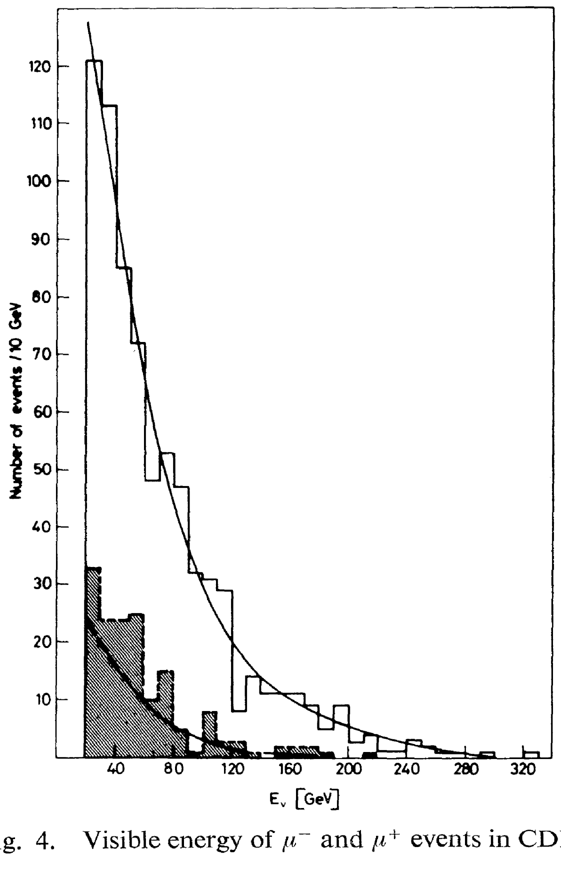

Fig. 4. Visible energy of μ^- and μ^+ events in CDHS

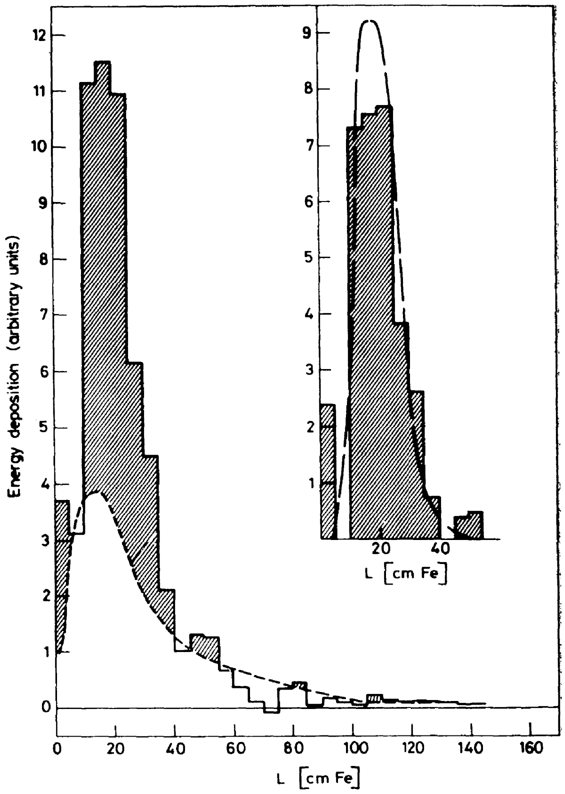

Fig. 5. Longitudinal shower development for excess muonless events; shape for hadronic showers (dashed curve); shape for non-hadronic showers (insert).

c) CDHS

The number of single μ^-, single μ^+, dimuon, trimuon, and muonless events observed for $E_{\rm vis}>20$ GeV is 850, 187, 6, 0, and 372, respectively. The absence of trimuon events puts an upper limit of 10% to the contribution of new particles to trimuon production in a wide band beam. The rate of dimuons $N(\mu^-\mu^+)/N(1\mu^-)=(0.7\pm0.3)$% agrees with the rate observed in the narrow band beam experiment, and the same is true for the kinematical distributions of dimuon events.

The visible energy spectra of μ^- and μ^+ events are shown in Fig. 4. A significant effect is observed in the muonless events: using the standard definition of muonless events in this detector, a number of 372 ± 30 muonless events (NC) is obtained while the number of charged-current events in the same fiducial volume is 435 ± 27 (CC). Using the measured ratio $NC/CC=0.3$, one expects 130 ± 20 ν_μ induced neutral current events, plus additional 45 ± 15 events from the known electron-neutrino contents of the beam. Therefore 197 ± 35 muonless events are due to a new source of prompt neutrinos. The longitudinal shower development of these excess muonless events is shown in Fig. 5, and is seen to be significantly different from the one for $\nu_\mu(\bar\nu_\mu)$-induced hadronic showers. According to this distribution, only (57 ± 10)% of the total energy deposition is due to hadron showers (including their π^0 component), the rest due to electromagnetic showers. This agrees with

Table II. Event ratios.

		BEBC $E_{vis}>10$ GeV e^-/μ^-	BEBC $E_{vis}>10$ GeV e^+/μ^+	CDHS $E_n>20$ GeV NC/CC	CDHS $E_{vis}>20$ GeV μ^+/μ^-	GGM $(e^-+e^+)/(\mu^-+\mu^+)$
Observed	0 mr	0.37 (11/30)	0.80 (4/5)	0.86 ± 0.08	0.22 ± 0.02	0.56 (9/16)
	15 mr	0.67 (8/12)				
Expected	0 mr	0.07	0.09	0.30 ± 0.01	0.14 ± 0.015	0.07
Basis for expectation		K and hyperon production and decays		Measured for ν_μ	π^-/π^+ production	

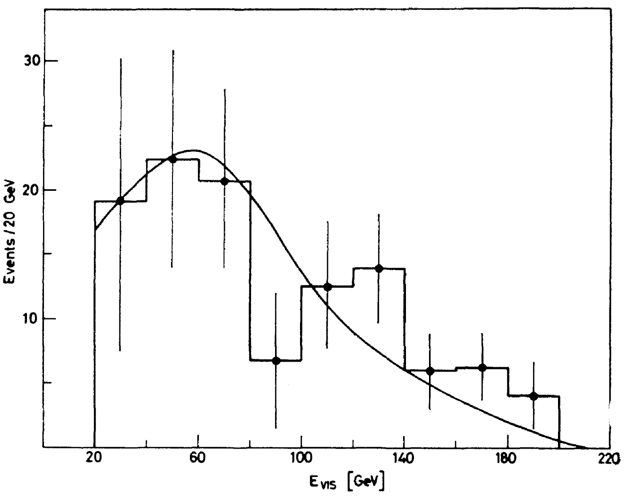

Fig. 6. Visible energy for ν_e charged current events. Line shows expectation for D→Keé, K*eν decays with equal branching ratios.

an interpretation of these events as originating from electron neutrinos, but not from τ neutrinos or axions, where essentially all energy would be deposited by hadrons.

Assuming a ratio $NC/CC=0.3$ and taking into account the cut $E_{vis}>20$ GeV, the prompt signal consists therefore of 171 ± 31 charged current and 26 ± 5 neutral current (ν_e, $\bar{\nu}_e$)-interactions. The visible energy spectrum of a sample of ν_e-charged-current events agrees with the expected shape if the electron neutrinos come from $D^0\to Ke\nu_e$ and $K^*e\nu_e$ decays with equal branching ratios (Fig. 6).

The evidence for prompt neutrino production in the three experiments at CERN is summarized in Table II.

d) *HPB Observations*

This experiment uses 28 GeV/*c* protons dumped into a copper dump in front of a massive (30 m deep) muon shield and concurrently measures normal neutrino events from neutrinos produced in a 15 cm bare Cu target 60 m upstream of the dump. The detector is a liquid scintillator calorimeter. The quantity measured in the experiment is $F=$ (Event rate from 15 cm target)/(Event rate from beam dump). If only conventional sources of neutrinos are considered, an involved calculation yields $F=57\pm12$. Experimentally, for neutrino-induced events, $F=33\pm4$ is observed. This result can be converted into event numbers, *i.e.*, the observed number of neutrino events in the beam dump runs, 104 ± 16 events, has to be compared to the expected number from the 15 cm target runs, 59 ± 13 events.

e) *IHEP/ITEP Observations*

A 70 GeV proton beam is dumped into an iron target of variable density, and particles penetrating through a 60 m Fe wall are detected in an Al-spark-chamber detector. Extrapolation to infinite target density gives a number of 69 ± 56 prompt ν_μ-events and 15^{+10}_{-12} prompt ν_e events. If, on the other hand, one takes the ν_e sample of 22 events having an e.m. shower with energy E>1 GeV starting directly from the vertex and no penetrating track longer than 72 cm of iron, and if one subtracts conventional backgrounds of ν_e originating from K, Λ, Σ decays (9 ± 2 events) and of ν_μ induced events with π^0 shower (8 ± 2.5 events), one arrives at a prompt event level of 5 ± 6 events.

The prompt neutrino flux into the 450 μsr solid angle of the detector is then $(N_{\nu_e}+N_{\bar{\nu}_e})=(2.7\pm2.2)\ 10^{-6}$/proton.

§3. Interpretations

a) *Background*

In the CERN experiments,[12] one can imagine a background source of electron neutrinos if a part of the proton beam would hit the beam pipe in such a way that the charged mesons produced are subsequently bent away, while K^0's can reach the detectors. In this case 0 mr data and 15 mr data should be the same,

Table III. Summary of results.

	BEBC	GGM	CDHS	BHP	IHEP/ITEP
$\sqrt{s}$ GeV	28	28	28	7.5	12
Excess events	11.3	7.3	236±40	45±21	11±9
Mean energy of excess events GeV	71	73	85	1.5	5
Prompt ν_e in solid angle $\Delta\Omega$ of detector per incident proton	5×10^{-7}	10^{-7}	$(1.9\pm0.4)10^{-7}$	$<7\times10^{-6}$*	$(2.7\pm2.2)10^{-6}$
$\Delta\Omega$	10 μsr	1.8 μsr	10.8 μsr	0.4 msr	0.45 msr
$N(\nu_e)/N(\nu_\mu$ from K)			0.43±0.09		
		Charm interpretation			
$(1-x_F)^n$	$3\lesssim n\lesssim5$	n=5	n=3		
exp $(-bp_t)$	$b\lesssim2$				
exp $(-\alpha p_t^2)$	—	—	$\langle p_t\rangle=0.7$ GeV/c		
σ (pp→D$\overline{\rm D}$+X)	100–200 μb	150±50 μb	40±8 μb		19±15 μb
		Axion search			
Axion events	0	—	<65	<66	<20
$\sigma(pp\to a_0+X)\sigma(a_0p\to X')$ [cm^4]	$<2\times10^{-67}$		$<10^{-67}$	$\lesssim3\times10^{-67}$*	$\lesssim4\times10^{-67}$*
n_{a_0}/n_{π^0}		$<10^{-8}$	$<5\times10^{-9}$		$<6\times10^{-9}$

* Calculated by the author.

since the upstream part of the narrow-band beam is the same as the wide band beam. However, the energy spectra observed in BEBC differ considerably in the two cases. The mean energy is 65 GeV for the 0 mrad data and 19 GeV for the 15 mrad data. Also the CDHS group finds no excess of wrong-sign muon events in the narrow-band beam above 50 GeV.

b) Prompt neutrinos from charm

The excess events are therefore most likely due to prompt ν_e production. The most direct result is the number of prompt electron neutrinos incident on the particular detector per incident proton. Table III summarizes these numbers. For the CERN 400 GeV experiments the measured signals are between (2–5) $10^{-8}\nu_e/\mu$sr. For the lower enegy experiments the sensitivity is smaller, and the experiments are compatible.

The most likely interpretation of this prompt neutrino source is then made in terms of associated charm production and decay. Since the detectors see only a small fraction ($\sim10^{-2}$) of the neutrinos from these reactions, the total charm production cross-sections obtained in this way depend sensitively on the assumptions made about the production mechanism. These assumptions are i) dominance of the reaction pp→D$\overline{\rm D}$+X, ii) production mechanism according to $Ed^3\sigma/dp^3\propto(1-x_F)^n$ exp $(-\alpha p_t^2)$ or $\propto(1-x_F)^n$ exp $(-bp_t)$, where E is the D meson energy, p_t its transverse momentum and x_F is the Feynman variable $x_F=p_L^{\rm cm}/p_{L\max}^{\rm cm}$; iii) branching ratio of D mesons into electrons $B=0.1$; iv) dependence of the cross-section on the number of nucleons as $A^{2/3}$. The parameter n characterizing the x_F-distribution is taken to be between $3\lesssim n\lesssim5$, and the transverse momentum distributions are such that $\langle p_t\rangle\propto0.7$ GeV/c.

With these assumptions, the charm production cross-sections in Table III are obtained. If the cross-section would depend linearly on A, the values would be smaller by a factor of 4.

These charm production cross-sections are compatible with upper limits obtained in FNAL experiments[6] searching for Kπ decays of D mesons, with a recent CERN–ISR experiment[7] quoting (70±36) μb and with the Caltech–Stanford experiment[8] on single μ production reported at this conference. However there is a very low upper limit from an emulsion experiment[9] which, for lifetime around 5×10^{-14} sec, quotes $\sigma<1.5\,\mu$b/nucleon. Taking into account[10] the detection efficiency of that experiment one obtains an upper limit to the cross-section as a function of the D lifetime, as shown in Fig. 7 together with the beam dump results. Agreement between all experiments can only be achieved if the lifetime is $\tau>8\times10^{-13}$ sec or $\tau<7\times10^{-16}$ sec.

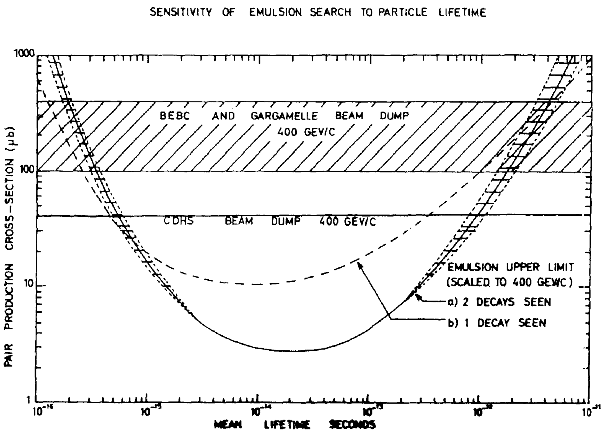

Fig. 7. Associated charm production cross-sections; curve: upper limit of emulsion experiment; lines: beam-dump experiments.

c) Axion search

The axion, a light scalar boson with semiweak interaction[11] would be produced in the beam dump and would simulate hadronic neutral current events in the detectors. The observed event numbers can be used to set upper limits to the production and interaction of this postulated particle, a_0. The upper limits to the product of production and interaction and cross-section of the axion are given in Table III. The lowest upper limit is $\sigma(pp \to a_0 + X) \cdot \sigma(a_0 p \to X') < 10^{-67}$ cm^4, while theoretical models give a lower limit of 9×10^{-66} cm^4 for this quantity. Similarly, the production rate of a_0 relative to π_0 mesons is found to be $n_{a_0}/n_{\pi^0} < 5 \times 10^{-9}$, while the model predicts $10^{-8} \lesssim n_{a_0}/n_{\pi^0} \lesssim 10^{-7}$. The axion hypothesis in its present form is therefore unlikely to survive experimental tests.

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B 7 Evidence for Prompt Single Muon Production in High Energy Proton Interactions

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Prompt leptons have been observed since 1974[1], and prompt lepton pairs from electromagnetic sources have been studied in several experiments.[2] We report here on the observation of a signal for single prompt leptons, whose source would be a weak decay.

The detector for the experiment sat in the N5 hadron beam at Fermilab. First came a PWC-dipole spectrometer for measuring the incident beam energy (the beam line was tuned for 400 GeV protons); then a 2 m long calorimeter made of steel scintillator sandwiches; then

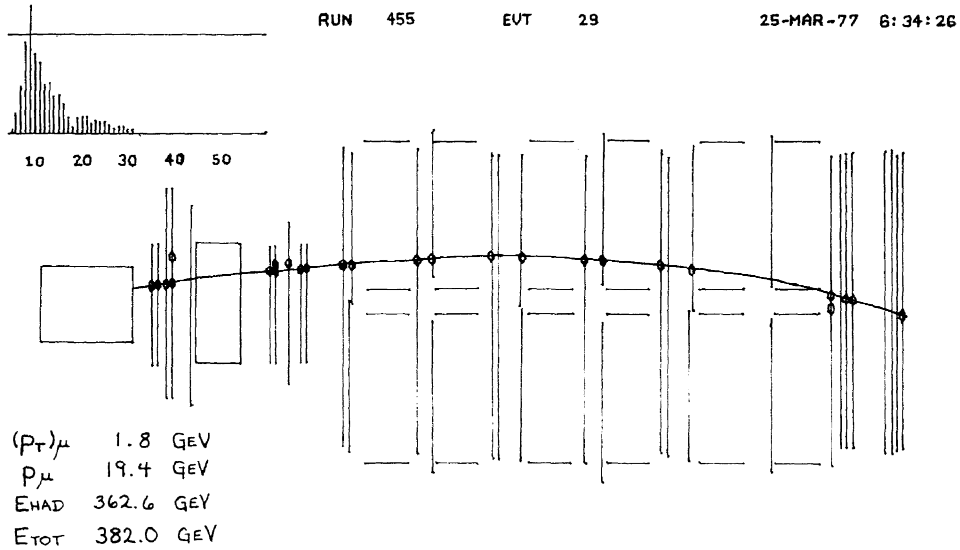

Fig. 1. An example of a single muon event in the detector. The vertical lines above the calorimeter indicate the longitudinal deposition of energy in the calorimeter.

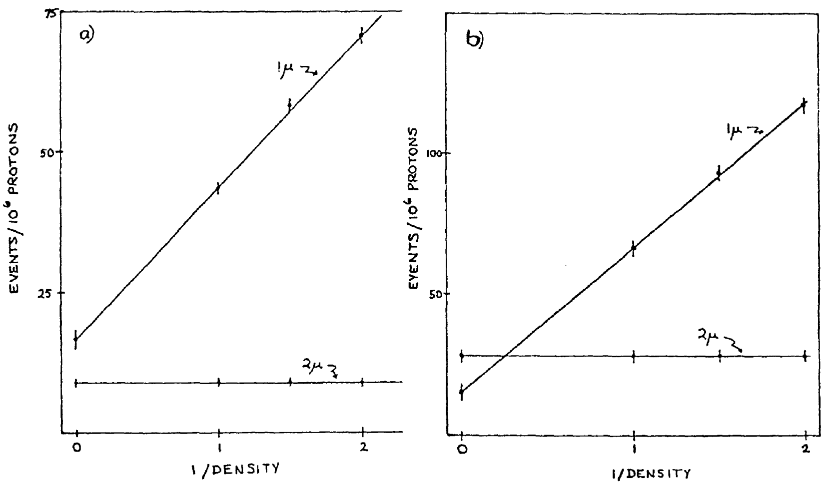

Fig. 2. Extrapolation plots to determine the prompt signal for events with 1 muon or 2 muons observed. Figure 2(a) shows the data for $p_t > 1.0$ GeV/c where a large single muon signal is observed; Figure 2(b) shows data for all p_t and $x_F > 0.05$ which also have a positive intercept.

spark chambers and a 1 m muon identifier. The energy of the emerging muons was measured in a 3.5 m diameter toroidal spectrometer, which could be positioned in different configurations which allowed for triggering on muons of either high p_t or high $p_{\|}$. A single muon event from the high p_t trigger is shown in Figure 1.

Decay muons from π's and K's were separated from the prompt signal by varying the effective density of the calorimeter-target by expanding the steel plates. Plotting the observed single muon rate as a function of inverse density $(1/\rho)$, we observe a positive intercept of many standard deviations at $1/\rho = 0$, corresponding to a prompt signal. This extrapolation is shown in Figure 2 for both kinematic regions. For comparison we show the rate of muon pairs, which should be independent of density.

One background for our signal is a muon pair event with one unobserved muon. The apparatus was designed with a very large acceptance for muon identification, so this background is small. Monte Carlo studies show that it is $\lesssim 10\%$ of the intercept. The other possible background would be from the decays of π's or K's which survive beyond the variable density portion of the calorimeter. Such a background would depend strongly in size on the interaction point within the calorimeter, varying by a factor of 2 over an interaction length. We observe no dependence of our signal on the interaction point.

One interpretation of our results is that the single muon signal comes from charm production. Assuming that the parent is the D(1865) meson decaying to $K\mu\nu$ and is produced with the same distributions we have measured for ψ's (*i.e.*, $dN/dx_F dp_t^2 \propto e^{-2p_t}(1-|x_F|)^5$), the observed prompt muon signal corresponds to a charm cross section of approximately 40 μb. We have taken the semileptonic branching ratio for D's to be 0.11 and used a linear A dependence for the production. It should be emphasized that the cross section is very sensitive to these assumptions and the estimate above can only be taken as an indication of the approximate level of the cross section.[3]

In conclusion, we have observed a substantial signal for single prompt muon production in high energy proton interactions. If all of this signal is due to charmed particles, a cross section level of 10–100 μb is indicated for the hadronic production of charm.

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3. The indicated cross section level is in qualitative agreement with recent measurments of prompt neutrino production in CERN neutrino beam dump experiments. Alibran *et al.*: Phys. Letters **74B** (1978) 134; Hansl *et al.*: Phys. Letters **74B** (1978) 139; Bosetti *et al.*: Phys. Letters **74B** (1978) 143. Our results appear higher than the quoted bounds on charm production from emulsion experiments, which might indicate that the lifetime is greater than 10^{-12} sec. G. Bertrand-Coremans *et al.*: Phys. Letters **65B** (1976) 480.

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B 7 A Short Review of Axions

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A short review of the theoretical motivations for axions, as well as their phenomenology and their present experimental status is presented.

Theoretical Background

The existence of nontrivial topological structures in QCD[1] implies that the quantum vacuum state is more complicated, being given by a superposition of an infinity of classically degenerate states[2]:

$$|\theta\rangle = \sum_{n=-\infty}^{\infty} e^{in\theta}|n\rangle \qquad (1)$$

The arbitary parameter θ, associated with the vacuum state, is a new parameter in QCD. It can be shown that the θ-vacua are equivalent to including an additional term in the QCD Lagrangian of the form[3]:

$$\mathscr{L}_\theta = \theta(g^2/32\pi^2)F_a^{\mu\nu}\tilde{F}_{a\mu\nu} \qquad (2)$$

Such a term is known to be a total derivative.[4] However, because of the topologically nontrivial structure of QCD it cannot be neglected.[3] Clearly, unless $\theta=0$ (or $\theta=\pi$) this term will induce strong P and T, and therefore CP, violations. This is not the only possible source of CP violations in the strong interactions. When the effects of the weak interactions are included the quark mass matrix, M, is in general not real. Thus the condition which is necessary for strong CP conservation is that

$$\bar{\theta} = \theta + \text{Arg det } M = 0 \qquad (3)$$

(Actually, as Baluni[5] has argued recently, the present bound on the neutron dipole moment only requires $\bar{\theta} \leq 10^{-8}$.) We should note that, because of the topological structure of QCD, Weinberg's[6] original argument for removing *CP* violations associated with the phase of the quark mass matrix is no longer valid. Although a chiral rotation can change Arg det M it also changes θ, because of the Adler–Bell–Jackiw anomaly,[7] in such a way that $\bar{\theta}$ remains fixed.

One can remove the threat of strong *CP* violations if the theory possesses an overall chiral U(1) symmetry.[8] Then $\bar{\theta}$ can be rotated to zero. Two possibilities can be envisaged for such an automatic strong *CP* conserving theory:

(1) The chiral symmetry obtains because one of the quarks—presumably the u quark—has zero mass

(2) The chiral U(1) symmetry is imposed by enlarging the weak symmetry group G to $G \times U(1)_{\text{chiral}}$

The first possibility appears to be ruled out by standard current algebra arguments.[9] However, there is still a bit of controversy on this matter.[10] The second possibility, which was the one advocated in ref. 8, was shown by Weinberg[11] and Wilczek[12] to imply the existence of a very light pseudoscalar boson—the axion.

Phenomenology of Axions

I shall briefly describe the phenomenological properties of axions in the standard SU(2)× U(1) model of the weak interactions[13] in which fermions are in left-handed doublets and right-handed singlets and all Higgs multiplets are SU(2) doublets. If these conditions are relaxed[14,15] one can alter some of the properties of axions in ways which could make them even more elusive. By including two Higgs doublets and suitably restricting their interactions one can enlarge the standard model to be $SU(2) \times U(1) \times U(1)_{\text{chiral}}$ symmetric.[8] Upon spontaneous breakdown an additional pseudo-Goldstone boson[11,12] appears which is associated with the extra chiral U(1) current:

$$J_\mu^5 = f\partial_\mu\phi + (x/2)\sum_i \bar{p}_i\gamma_\mu\gamma_5 p_i + (1/2x)\sum_i \bar{n}_i\gamma_\mu\gamma_5 n_i + (1/2x)\sum_i \bar{l}_i\gamma_\mu\gamma_5 l_i \tag{4}$$

Here ϕ is the axion field, p_i are charge 2/3 quark fields, n_i are charge $-1/3$ quark fields and l_i are charge -1 lepton fields. The parameter f is related to the Fermi constant:

$$f = (\sqrt{2}G)^{-1/2} \simeq 250 \text{ GeV} \tag{5}$$

while x—which is related to the ratio of Higgs expectation values—is a free parameter of the theory and is presumably of O(1).

The axion would be a real zero mass Goldstone boson were it not for the fact that J_μ^5 has an anomaly. Its mass and its principal properties can be derived by constructing an anaomaly free current which is soft—that is a current whose divergence vanishes when m_u and/or m_d vanishes.[11,16–18] One finds

$$m_a = m_\pi \frac{f_\pi}{f} N\left(x + \frac{1}{x}\right)\frac{Z^{1/2}}{1+Z} \simeq 25N\left(x + \frac{1}{x}\right)\text{keV} \tag{6}$$

and[17]:

$$\tau_{a\to 2\gamma} \simeq 0.8(100 \text{ keV}/m_a)^5 \text{ sec} \tag{7}$$

Here N is the number of quark doublets and and $Z = m_u/m_d \simeq 0.56$.[9] We should note that if $m_a > 1$ MeV the axion could also decay into e^+e^- pairs with a lifetime[11,12] of the order of 10^{-8}–10^{-9} sec. Using strandard current algebra methods one can also determine the coupling of axions to nucleons and leptons. One finds[11,17,19]

$$\mathscr{L}^{\text{eff}} = i\phi\{\bar{N}\gamma_5(g_0 + g_1\tau_3)N + \sum_i \bar{l}_i\gamma_5 g_{l_i} l_i\} \tag{8}$$

where

$$g_0 = g_{aNN}(\tfrac{3}{5})(N-1)(x+1/x) \tag{9}$$

$$g_1 = g_{aNN}\left\{x\left[1 - N\frac{(1-Z)}{(1+Z)}\right] - \left[\frac{1}{x} + \frac{N}{x}\frac{(1-Z)}{(1+Z)}\right]\right\} \tag{10}$$

$$g_{l_i} = m_{l_i}(1/xf) \tag{11}$$

$$g_{aNN} = \tfrac{1}{2}(f_\pi/f)g_{\pi NN} \simeq 2x10^{-4} g_{\pi NN} \tag{12}$$

Experimental Test of Axions

I shall discuss three different experimental tests for axions:

(*1*) *Decays*

The process $K \to \pi a$ has been analyzed theoretically by a number of authors[11,20–22] and compared to the experimental bound[20] coming from the search for the process $K^+ \to \pi^+\nu\bar{\nu}$:

$$\frac{\Gamma(K^+ \to \pi^+ a)}{\Gamma(K^+ \to \text{all})} < 2.7 \times 10^{-7} \tag{13}$$

Unfortunately, the theoretical estimates are quite model dependent, yielding branching ratios ranging from 10^{-5} to 10^{-8}, and thus are not immediately useful. Wilczek[12] has suggested looking for axions in ψ decays. He computes

$$\frac{\Gamma(\psi\to a\gamma)}{\Gamma(\psi\to e^+e^-)}=\frac{G}{\sqrt{2}\pi\alpha}m_c^2x^2\simeq 7\times10^{-4}x^2 \quad (14)$$

This should be testable shortly with forthcoming SPEAR data. In the future Υ decays, because of the higher mass of the b-quark, may provide an even more stringent test.

(*2*) *Reactor experiments*

Axion production by nuclear reactors ,and their possible experimental detection in experiments carried out by Reines and collaborators,[23] has been analyzed by Weinberg,[11] Feinberg,[24] Micelmacher and Pontecorvo[25] and by our group at Stanford.[19] The analysis is made difficult because of uncertainties in estimating the axion flux from the Savannah River reactor. Below I shall quote results based on the axion flux estimated by the Stanford group[19] of 2×10^5 axions/cm^2-sec. Greater fluxes, ranging to 2×10^7 axions/cm^2-sec, have been estimated by other authors. Axions could have been a source of γ background in the 1976 experiment of Reines *et al.*[23] This background is given as (-160 ± 260) events/day for $E_\gamma>1.5$ MeV and is estimated again to be zero but with a larger standard deviation ($\sim10^3$ events/day) for all E_γ.[26] From the process $a\to2\gamma$ we estimated[19] a γ-background of 7×10^3 $(m_a/100\text{ KeV})^6$ events/day for all E_γ and 1/5 this number for $E_\gamma>1.5$ MeV. Additionally the process $ae\to e\gamma$ would produce $\sim10^3/x^2$ events/day. Clearly, unless $m_a\simeq100$ KeV and $x\simeq1$ the axion is in serious trouble. The 1974 experiment of Reines *et al.*[23] is even more problematic. Here the process searched for $(\bar\nu_e d\to np\bar\nu_e)$ could be mimicked by deuteron disintegrations of axions with $E_a>2.2$ MeV. Experimentally the number of neutron counts is given as (-2.9 ± 7.2) events/day. Axions are estimated to produce $\sim4\times10^3$ events/day by the Stanford group[19] while an even higher rate is given by Weinberg[11] and Feinberg.[24] This is surely very bad for axions. Two caveats ought to be mentioned, however. If the axion spectrum is suppressed with respect to the γ-spectrum at high energy the rate quoted above is reduced. Further, if the axion were essentially isoscalar $(g_1\simeq0)$ axion deuteron distintegration would also be dynamically suppressed.

(*3*) *Beam dump experiments*

These experiments have been analyzed by Ellis and Gaillard[27] and in ref. 19. Here the production and detection of axions is more amenable to direct calculation. There are four relevant experiments:

a) SLAC beam dump[28]: The production of axions is by a bremsstrahlung process, $eZ\to eZa$, which is calculable.[19,21] Axions are detectable through μ-pair production—which is again calculable[19,21]—or by producing hadronic showers. This latter process can be estimated to occur at a rare $(g_{aNN}/g_{\pi NN})^2B_\pi^2\simeq4\times10^{-8}B_\pi^2$ times a typical π^0 induced hadronic shower, with B_π^2 an unknown parameter of O(1). The analysis of ref. 19 estimates that $5.5/x^4$ μ-pairs and $\sim200\,B_\pi^2/x^2$ hadronic showers should have been seen. Experimentally no μ-pairs and 3 or less hadronic showers were observed. For $x\simeq1$ this implies $B_\pi^2<0.03$ which is well below expectations. (For an argument suggesting $B_\pi^2\simeq10^{-3}$ see, however, ref. 21).

b) CERN beam dump experiment[29,30]: Here the production and detection is hadronic, although the CDHS experiment also looked for axion induced μ-pairs.[30] The quoted numbers on the product of production times detection cross sections ($\sigma_p\sigma_i<2\times10^{-67}$ cm^4,[29] $\sigma_p\sigma_i<10^{-67}$ cm^4 [30]) yield $B_\pi^2<0.12$ consistent with the SLAC result.

c) BNL beam dump experiment[31]: This recent beam dump experiment gives the limit $\sigma_p\sigma_i<10^{-68}$ cm^4 which implies $B_\pi^2<0.04$, again in agreement with the other beam dump experiments.

Concluding Remarks

The above analyses are quite discouraging for the axion idea. However, perhaps it is well to remember that almost all the experiments discussed have quite a bit of theoretical uncertainty in their interpretation. As an example we remark that if $m_a>1$ MeV then probably the reactor bounds are irrelevant, since the axion flux would be drastically reduced by phase space arguments. (The beam dump experiments, however, are still relevant). Now m_a can be large if x or $1/x$ is large. The latter is excluded by the SLAC beam dump experiment, while the former would imply a large rate for $\psi \rightarrow a\gamma$. Thus results from this latter experiment are quite important. Equally important, perhaps, is to look for axions in theoretically clean experiments like axion production by intense low energy electron machines[19,21] and with detection through γ-decay.

In view of the quite strong evidence against axions it is obviously also useful to look for alternative theoretical solutions to the *CP* problem, which do not rely on axions. At present, however, only some rather tentative ideas exist. Some of these ideas are discussed in Weinberg's report at this Conference[32] as well as in my report at the Singapore Conference.[33]

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