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Experiments on rare processes at TRIUMF

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Since it first delivered high-intensity beams in 1975, TRIUMF has had a program of research in particle physics based upon the study of rare processes. The interest for these kind of activities is based upon the testing of the successful standard model of electroweak interactions, with the hope of getting a glimpse at physics beyond the standard model.

I shall describe four of the recent experiments in this field which are either in the final stages of analysis or in the data-taking phase. They are:

- The measurement of the $\pi \to e\nu/\pi \to \mu\nu$ branching ratio as a test of electron-muon universality
- The search for muonium-antimuonium conversion searching for doubly charged Higgs-like objects
- The first measurement of radiative muon capture on hydrogen and a measurement of the induced pseudoscalar coupling constant g_p
- A search for the decay $K^+ \to \pi^+ +$ "nothing" conducted by a TRIUMF team at the Brookhaven Alternating Gradient Synchrotron, which tests predictions of the standard model in a pure second-order weak process

1. Measurement of the $\pi \to e\nu/\pi \to \mu\nu$ branching ratio*

The goal of the experiment is a very precise determination of the branching to a level of 0.3%, which is slightly above the level of precision of the theoretical predictions, assuming conventional wisdom such as massless neutrinos, lepton universality and pure V-A effective weak interaction. Any significant deviation from this prediction would signal new physics beyond the standard model.

This experiment has been performed several times since the first beam hit the π production targets in 1975 and is typical of the long, tedious process that one has to go through when dealing with experiments at the precision frontiers.[1]

Within the assumptions mentioned above, the prediction for $R_0 = \dfrac{\Gamma(\pi^+ \to e^+\nu_e)}{\Gamma(\pi^+ \to \mu^+\nu_\mu)}$ is

$$R_0 = \left(\frac{f_\pi^e}{f_\pi^\mu}\right)^2 \times \frac{m_e^2}{m_\mu^2}\,\frac{(m_\pi^2 - m_e^2)^2}{(m_\pi^2 - m_\mu^2)^2} = \left(\frac{f_\pi^e}{f_\pi^\mu}\right)^2 \times 1.2835 \times 10^{-4}\,,$$

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*The experimental team was composed of S. Ahmad, G. Azuelos, D. Britton, D. Bryman, T. Clifford, Y. Kuno, J. Macdonald, T. Numao, A. Olin and J-M Poutissou from TRIUMF, P. Kitching from Univ. of Alberta, and M. Dixit from the National Research Council.

[redacted]

where f_π^ℓ are the decay constants associated with the electron or the muon branch. The electron-muon universality hypothesis implies the identity of f_π^e and f_π^μ. However, this ratio is substantially modified by radiative corrections.

Experimentally also one is measuring a slightly different quantity because of the detector's ability to pick up the associated radiative photons.

$$R_{\rm expt} = \frac{\Gamma(\pi^+ \to e\nu_e + \pi^+ \to e^+\nu_e\gamma)}{\Gamma(\pi^+ \to \mu\nu_\mu + \pi^+ \to \mu^+\nu_\mu\gamma)} \ .$$

Theoretically[2] one has: $R_{\rm corr} = R_0(1+\delta)(1+\epsilon) = 1.2345 \times 10^{-4}$, where δ and ϵ are the contributions from radiative corrections of −3.75% and −0.2%. The contribution from structure-dependent terms provides the dominant source of uncertainty in the theoretical prediction which is now estimated to be of order 0.08%.

The technique used in this experiment relies on the measurement of the energy spectra for positrons emitted via the $\pi \to e\nu_e$ mode or the $\pi \to \mu \to e^+$ decay sequence with a large NaI detector which has 100% detection efficiency over a large energy region. By comparing spectra obtained within two different time bins, one positioned very soon after the pion has stopped, the other several pion lifetimes away from it, one is able to reduce the level of systematic errors. In Fig. 1 the experimental set-up is schematically presented. The lower part of the figure shows the new target assembly used. In the latest version of this experiment, one was trying to reduce the dominant source of error in our 1980 measurements, which was the knowledge of the low-energy tail of the NaI response function.

As is shown in Fig. 2, the monoenergetic positron from $\pi \to e\nu$ appears as a broad line at 70 MeV/c. About 2% of the events are confused under the broader spectrum from muon decay. A very careful estimate of the lineshape response of the NaI has to be made to extract that component.

By measuring the energy release in the stopping counter, one is able to measure an upper limit to this tail contribution, thereby reducing the reliance on the Monte Carlo estimate. Still a contamination from the muon-induced positron remains, but is small enough to establish the number of lost $\pi e\nu$ events below 52.3 MeV to a precision of ±0.3%.

Table I gives the various correction factors entering in the calculation of the branching ratio and the associated uncertainty contributions. The tail uncertainty has been reduced to a level of 0.3% compared to 0.75% in our previous attempt. At this stage of the analysis, conservative estimates are quoted and further analysis should lower this estimate to about 0.2%. If this is obtained, the goal of the experiment will be reached.

Using the preliminary estimates, it is possible to establish the ratio of the decay constants for the electron and muon decay mode as:

$$\frac{f_\pi^e}{f_\pi^\mu} = 0.9990 \pm 0.0022 \qquad \text{(very preliminary)}\ ,$$

which fail to show any deviation from e-μ universality.

If one assumes universality and allows for nonV-A contributions, then one can set a limit for a possible pseudoscalar contribution as:

$$f_p \simeq (-0.0010 \pm 0.0022) f_\pi\, m_e \ .$$

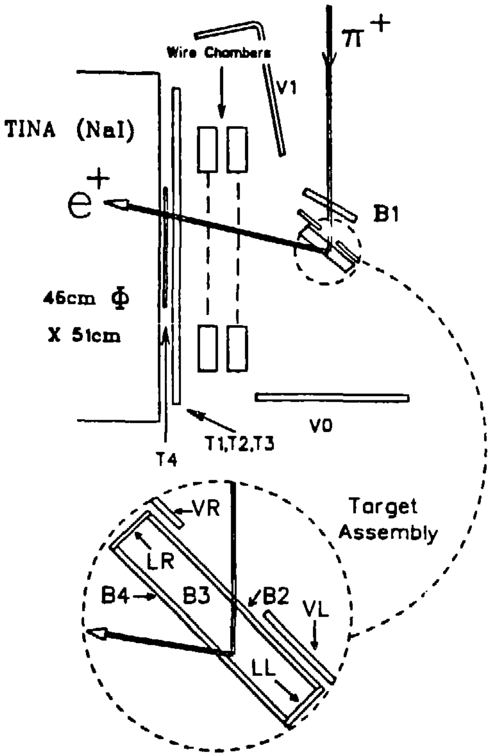

Fig. 1. Schematic diagram of experimental apparatus.

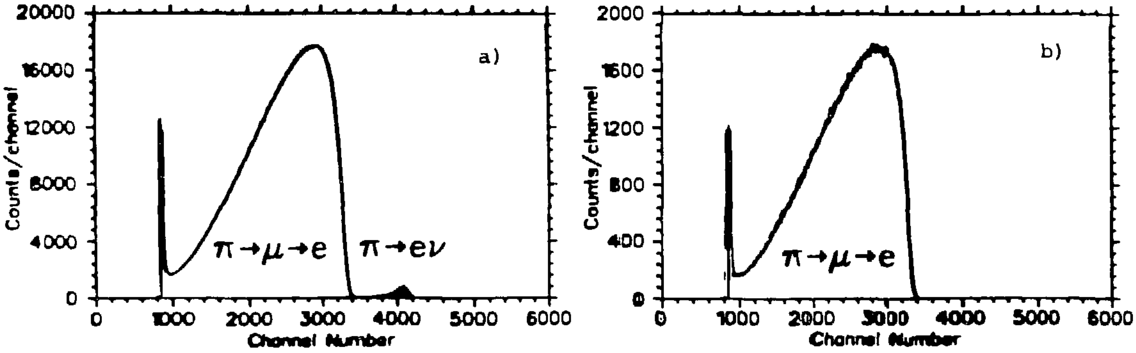

Fig. 2. (a) BIN1 (b) BIN2 TINA energy spectrum.

Table I. Multiplicative corrections to the branching ratio and associated errors.

	Correction	Uncertainty
Statistics (binning method)	–	0.0036
Statistics (timing method)	–	0.0028
Tail correction	1.0182	0.0030
Multiple scattering + annihilation in flight + low-energy trigger losses	1.0022	0.0020
t_0 energy dependence	0.9998	0.0008
False vetos	1.0003	0.0023
Wire chamber efficiency	0.9998	0.0004
T/B-pu interference	0.9995	0.0005
Pion lifetime	–	0.0009
Bin1–Bin2 equality	1.0001	0.0001

The same experiment can be exploited to search for exotic decay modes, for example, decays into heavy hypothetical neutrino mass states. Such decay modes would manifest themselves as monoenergetic peaks (with similar lineshape as the main $\pi e\nu$ peak) but located at lower energy than for the case of zero mass neutrinos. Due to the relaxation of the helicity suppression factor $(m_e/m_\mu)^2$, this reaction is extremely sensitive and very strong limits have been put on the coupling of such states. Figure 3 indicates the improvements which have been obtained in the latest experiment (curve 3) compared to previous analyses by our group.

A search for heavy scalar particles has been made in the range of 0–139 MeV. The limits obtained are shown in Fig. 4.

Within a few months a final branching ratio will be obtained, and the long, arduous work of our graduate student, D. Britton,[5] will have paid off.

2. Search for muonium-antimuonium mixing*

This experiment is more characteristic of the rare decay searches which have preoccupied a large fraction of our physicists over the last decade; it looks for a process which is forbidden in the minimal standard model and its discovery would clearly point to some extension of the model.

In this particular case, there is a very compelling argument to extend the standard model to a left-right symmetric theory in which parity violation occurs via spontaneous breaking of this symmetry.[6] In these theories muonium and antimuonium mix through the exchange of a doubly charged Higgs particle. For a certain range of the model's parameters, observable rates are predicted.

A dramatic improvement on this search has been realised at the meson facilities, due to the discovery of a very efficient way of producing muonium in vacuum.[7] To

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*Collaboration from Univ. of Victoria (G. Beer, A. Jamissen, G. Mason, A. Olin – spokesman), Univ. of Wyoming (T. Huber, A. Kunselman), Univ. of Arizona (T. Bowen, P. Halverson, K. Kendall), Univ. of British Columbia (J. Warren – deceased).

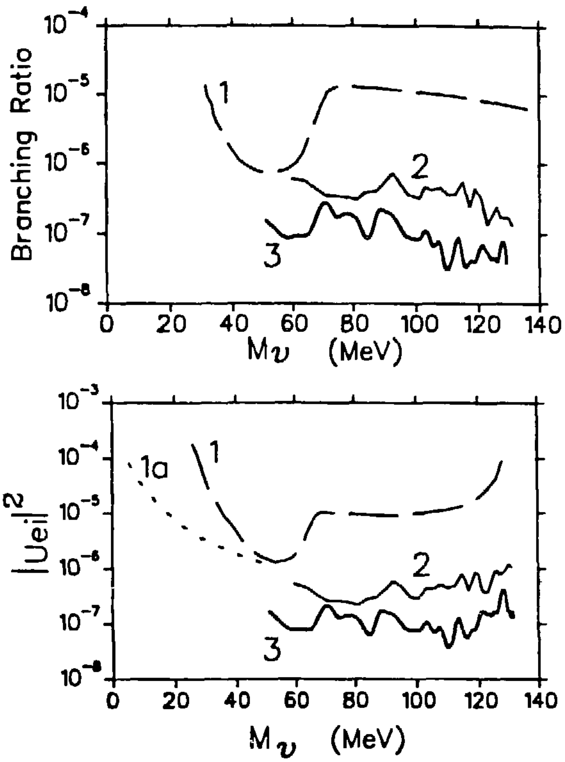

Fig. 3. Limits on massive neutrinos: The upper plot shows the limits on the branching ratio $\pi \to e, \nu_i / \pi^+ \to \mu^+ \nu_\mu$; the lower plot shows the corresponding limits on the mixing parameter $| U_{ei} |^2$. Curves 1 are from Ref. 3; curves 2 are from Ref. 4; and curves 3 are from the present work.

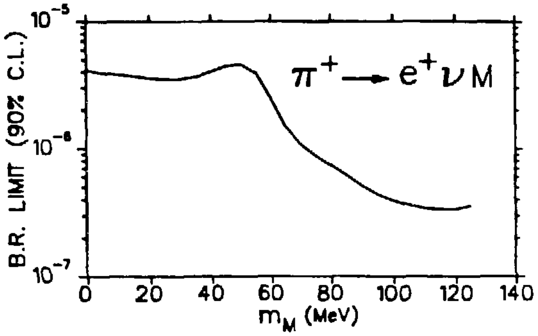

Fig. 4. Branching ratio limits for $\Gamma(\pi^+ \to e^+ \nu_e M)/\Gamma(\pi^+ \to \mu^+ \nu_\mu)$.

recognize the antimuonium atom, various techniques have been used so far, mainly based on the detection of the presence of a μ^- in the final state. Here a clever use of nuclear physics is exploited: the μ^- is captured on an element W which then forms ^{184}Ta. This element has a very characteristic decay scheme where one can use the coincidence between a β-ray and a prompt 414 keV gamma-ray followed by a delayed emission of gamma-rays from the metastable state formed (see Fig. 5).

Figure 6 describes the experimental apparatus. Muonium is formed by stopping "surface" muons into a thin layer of SiO_2 powder. It diffuses out of the surface at thermal velocities and travels in a field-free region in a 10^{-8} torr vacuum. If conversion takes place in the drift space, a μ^- will be striking the tungsten catcher surface and could then be identified through the ^{184}Ta decay schemes. After an 8 h exposure the surface of the catcher is removed chemically and transferred to a low background counting apparatus away from the experimental area.

Table II presents a compilation of the most recent results from this group. After stopping 2.3×10^{12} μ^+, an upper limit of 2×10^{-6} was obtained for the branching ratio of muonium-antimuonium conversion over normal muon decay. However, this technique is starting to be limited by background from neutron-induced activity in the detector system, and further progress will resort to a coincidence tracking of both μ^- and e^+ in magnetic spectrometers. Such experiments are in progress at LAMPF[8] and proposals have been accepted at PSI.[9]

Table II. Experimental results.

Published results from November–December 1987 run

T.M. Huber *et al.*, Phys. Rev. Lett. **61**, 2189 (1988)

Total of $N_\mu = 4.0\times 10^{11}$ μ^+ during 100 h

$$\rho = \frac{\Gamma(\mu^+ e^- \to \mu^- e^+)}{\Gamma(\mu^+ \to e^+ \nu\nu)} < 2\times 10^{-5}$$

$$G < 0.88\, G_F \qquad (90\%\ \text{C.L.})$$

Result of summer 1988 run

Total of $N_\mu = 2.3\times 10^{12}$ μ^+ during 600 h

$$\rho < 2\times 10^{-6}$$

$$G < 0.28\, G_F \qquad (90\%\ \text{C.L.})$$

Constraint on left-right symmetric models

$$\frac{f^*_{\mu\mu} f_{ee}}{g^2} \cdot \left(\frac{M_W}{M_{++}}\right)^2 \sim \frac{G}{G_F} < 0.28$$

For $f^*_{\mu\mu} = f_{ee} = g$, limit on doubly charged Higgs Δ^{++} mass is

$$M \gtrsim 150\ \text{GeV}/c^2$$

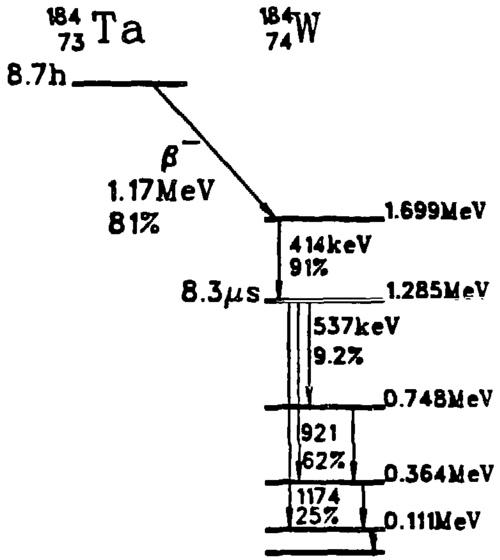

Fig. 5. Partial decay scheme of ^{184}Ta.

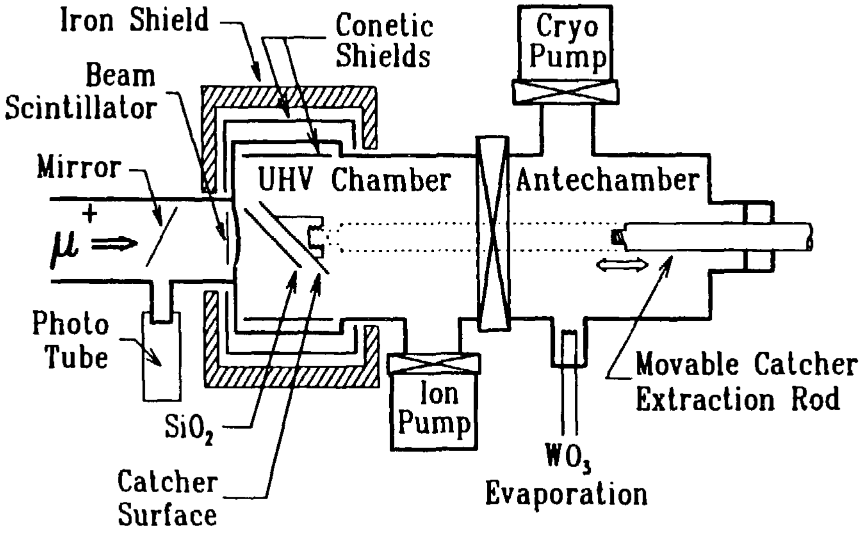

Fig. 6. Schematic diagram of experimental apparatus.

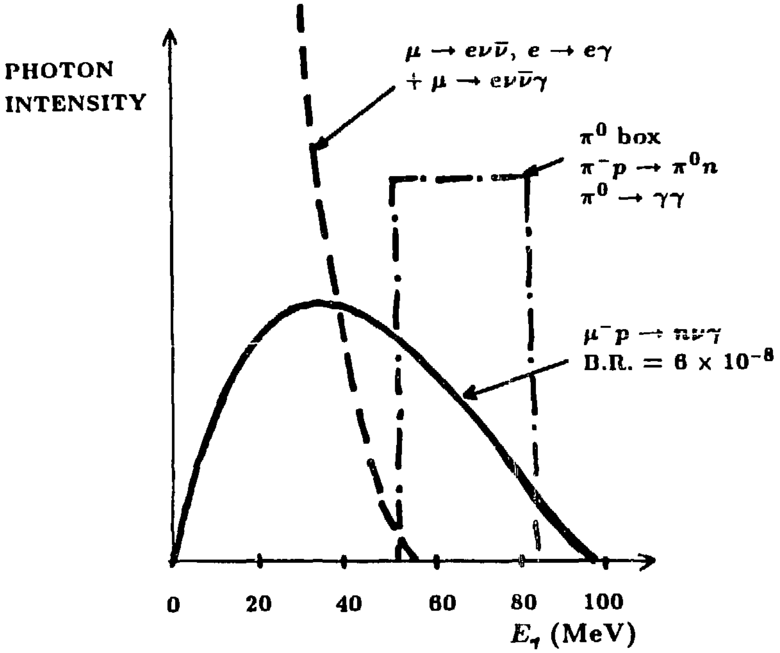

Fig. 7. RMC photon energy spectrum.

One can expect to reach the region where severe constraints on the left-right symmetry model will be placed (improvement of 4 orders of magnitude in the present branching ratio limit).

3. Radiative muon capture on hydrogen*

This rare process has eluded experimenters so far and should permit an independent precision measurement of the induced pseudoscalar coupling constant g_p on a nucleon. g_p has been deduced from ordinary muon capture but the error of all combined experiments so far is of order 40% and doesn't allow a good test of the Goldberger-Treiman relation between g_A, g_p, and f_π, the pion decay constant. Recently the contribution of $\Delta(1230)$ has been shown to be important and may resolve the possible discrepancy.[10]

Radiative muon capture is more sensitive to g_p than ordinary muon capture by a factor 3 due to the range of momentum transfer covered which can reach $-m_\mu^2$, a value considerably closer to the pion pole than that in ordinary muon capture ($0.88\ m_\mu^2$). The price to pay is in the rate of high-energy photons since the branching ratio for photons larger than the 53 MeV is only 6×10^{-8}.

In Fig. 7 the main sources of high-energy photons are shown. Radiative muon decay and external bremsstrahlung of decaying electrons contribute photon energies up to 53 MeV and due to detector resolution can induce background up to about 60 MeV. This limits the useful range of the radiative muon capture spectrum to a lower limit of about 60 MeV. In the region from 55 to 83 MeV, photons from neutral pions can be observed, and this dictates that the pion (π^-) contamination in the beam

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*Collaboration of Univ. of British Columbia, TRIUMF, Univ. of Melbourne, Virginia Polytechnic Inst., PSI, Université de Montréal, Queen's University and IHEP, Beijing.

must be reduced. In our experiment an rf separator[11] is used which lowers the number of π^- entering the hydrogen target by a factor 10^4. Because of the low rate of RMC photons, a high stopping rate of μ^- must be obtained. In the newly rebuilt M9 channel we can stop 5×10^5 μ^-/s in a 3 ℓ hydrogen cylinder.

The purity of the hydrogen gas is quite important because of the transfer probability of the muon to heavier elements, where it captures more readily (capture probability is proportional to Z^4). Also the transfer rate to deuterium is extremely large and the deuterium contamination must be kept under one part per million. A special flask is being built which allows for a bakeout procedure to outgas the wall, and by using a heavy Z material one can limit the capture gamma-rays from strayed muons ending in the wall to the earlier time and remove them via a timing cut.

Earlier attempts to measure radiative muon capture in nuclei have been plagued by background related to the large neutron contamination which comes from ordinary and radiative captures. To satisfy the above requirement on the resolution and insensitivity to neutrons, a large acceptance pair spectrometer has been built which uses a low mass, 1 m long, 4-layer drift chamber to track the electron-positron pairs produced in a 1 mm lead converter. The whole system is housed in a 2.7 kG magnetic solenoid. A side view of the detection system is shown in Fig. 8.

Production of ultra-pure hydrogen (<1 ppm d contamination) is under way by electrolysing ultra-pure water supplied by ISOTEC.*

So far the detection system has been commissioned by studying radiative muon capture on nuclei (C, O, Al, Si, Ca, Mo, Sn, Pb) and by stopping π^- in ordinary liquid hydrogen. The analysis of the π^- data showed that the resolution for monoenergetic gamma-rays (FWHM 8% at 129 MeV) and the high-energy tail behave as predicted by our Monte Carlo simulation. Our acceptance is also well predicted (0.65% at 65 MeV), and further studies are under way to improve it by loosening our triggering requirements and allowing events where only one of the two tracks reaches the external trigger scintillators. We are confident that our on-line software can cope with the increased trigger rate.

The goal of the experiment is to accumulate 400 high-energy gamma events above 57 MeV which should provide a ±10% measurement of g_p. First data-taking for the ultra-pure hydrogen is scheduled for the summer of 1990.

Because of the large acceptance, the detector is also a very promising π^0 detector, and plans are under way to improve the converter package with the objective of minimizing the energy losses in the inactive converter.

4. Study of the decay $K^+ \rightarrow \pi^+$ "nothing"†

Part of the TRIUMF group who had been involved in rare decay studies of pions and muons has taken a very active role in a rare kaon decay experiment at the Brookhaven AGS accelerator. Of course, this is not independent of the motivation behind our KAON project which would use the present TRIUMF cyclotron as an

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*ISOTEC Inc., 3858 Benner Road, Miamisburg OH 45342 FAX:(513) 859-4878.

†Experiment 787 at the Brookhaven AGS by a collaboration from Brookhaven (M. Atiya, I-H Chiang, J.S. Frank, J.S. Haggerty, M.M. Ito, T.F. Kycia, K.K. Li, L.S. Littenberg, A. Stevens, R.C. Strand), Los Alamos (W.C. Louis), Princeton (D. Akerib, D. Marlow, P.D. Meyers, M.A. Selen, F.C. Shoemaker, A.J.S. Smith), TRIUMF (G. Azuelos, E. Blackmore, D. Bryman, L. Felawka, P. Kitching, Y. Kuno, J.A. Macdonald, P. Padley, J-M Poutissou, R. Poutissou, J. Roy, R. Soluk, A. Turcot).

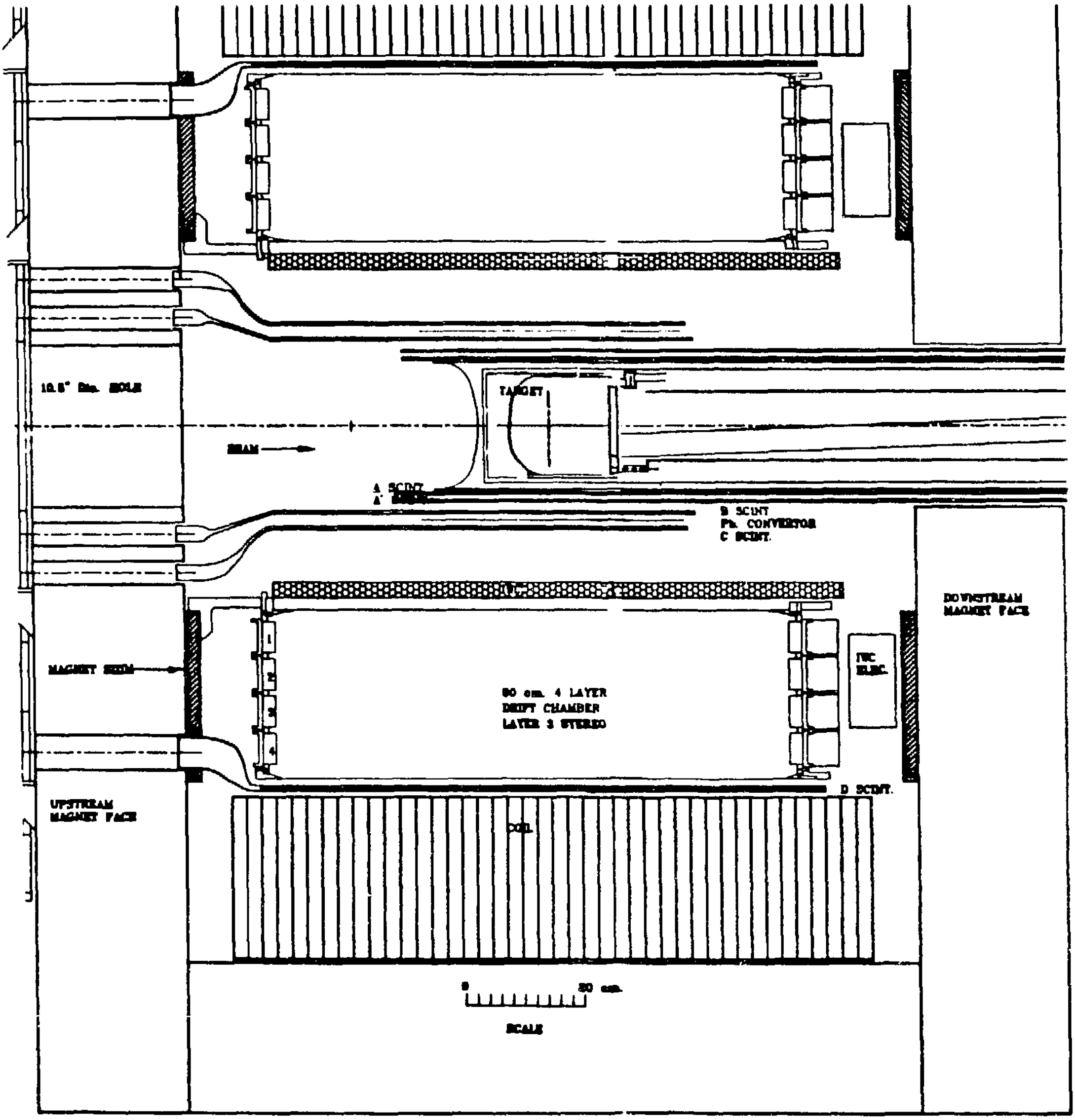

Fig. 8. Side view drift chamber installation in Chicago magnet.

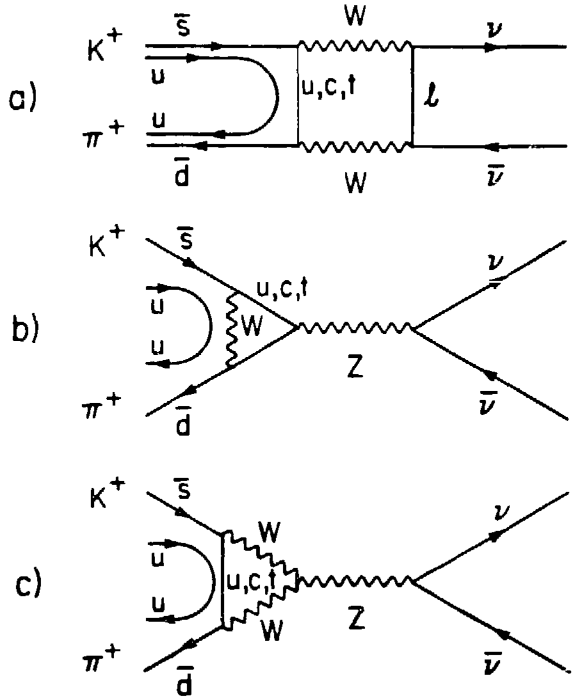

Fig. 9. Second-order diagrams for $K^+ \rightarrow \pi^+\nu\bar{\nu}$ (short-distance contribution).

injector for a 30 GeV, 100 μA accelerator complex. Also the physics motivation for this experiment is closely related to our previous efforts at TRIUMF. This will be a very succinct report to bring you up to date on the recent developments. A more detailed account of this work can be found in several recent publications.[12,13]

The decay $K^+ \rightarrow \pi^+\nu\bar{\nu}$ is a flavour-changing neutral weak interaction which proceeds via second-order weak diagrams like the ones depicted in Fig. 9 because of the strong suppression of the GIM mechanism. When observed this rare process will represent a crucial test of the standard model at higher orders. Since the final-state leptons are neutrinos, long-range effects are very small (unlike the analogous case, $K_L \rightarrow \mu^+\mu^-$) and consequently quite firm predictions can be made in the standard model framework.

The branching ratio is given by the expression:

$$\mathrm{BR}\left(\frac{(K^+ \rightarrow \pi^+\nu_i\bar{\nu}_i)}{\text{all } K^+ \text{ decays}}\right) = \frac{0.61 \times 10^{-6}}{\mid V_{us} \mid^2} \left| \sum_{j=c,t} V_{js}^* V_{jd} D(x_j) \right|^2$$
$$= 0.61 \times 10^{-6} \left| D(x_c) + \frac{V_{ts}^* V_{td}}{V_{cs}^* V_{cd}} D(x_t) \right|^2 ,$$

where $x_i = m_i^2/m_w^2$ and V_{ij} are the parameters of the Kobayashi-Maskawa matrix describing the mixing in the quark sector.

The rate is almost proportional to the number of light ν families (which is now limited, 3.1±0.1, by LEP and SLC experiments). For reasonable values of V_{ts} and V_{td} one expects the contribution from the heaviest charge = 2/3 quark to dominate; hence the sensitivity of the branching ratio to m_t. The lepton part of the rate estimate is largely independent of the lepton mass appearing in the box diagram.

Severe constraints are now available on the V_{ij} elements of the K-M matrix, and this turns into a specific prediction for the branching ratio which should be between 2 and 8×10^{-10}. Any appearance of a larger rate would signal new physics beyond the minimal standard model.

To reach the level of sensitivity of 2×10^{-10}, a new detector has been commissioned which can operate at the rate of stopping kaons which will be soon available after the booster upgrade of the AGS. The detector shown in Fig. 10 is designed to track precisely and identify the only charge product in the final state, the π^+, and reject the more copious events which could be mistaken for π^+ from the $K \rightarrow \pi^+\nu\bar{\nu}$ branch. 4π rejection of photons suppresses the $K^+ \rightarrow \pi^+\pi^0$ branch by a factor of 10^{-6}, while transient digitizers allow a positive identification of the π^+ through its decay sequence into a μ^+ and then an e^+, reducing drastically the contribution of $K^+ \rightarrow \mu^+\nu_\mu$ and $K^+ \rightarrow \mu^+\nu_\mu\gamma$, where a μ^+ could be misidentified as a π^+.

Energy, momentum and range are measured with σ resolution of 2% and a tracking stopping target made of scintillating fibres 2 mm in diameter helps select potential $K \rightarrow \pi\nu\bar{\nu}$ candidates.

The experiment had an engineering run in 1988 which produced an upper limit for the branching ratio of 3.4×10^{-8} (Ref. 14). A long data-taking run took place in 1989 and should have a sensitivity of a few 10^{-9} for 1 event candidates. Further running is scheduled for 1990. The present experimental situation is described in Table III.

Table III. Summary

Decay	Limit	Status
$K \rightarrow \pi^+\nu\bar{\nu}$	$<3.4\times10^{-8}$	published (Ref. 14)
$\pi^0 \rightarrow \nu\bar{\nu}$	$<1\times10^{-6}$	preliminary
$K \rightarrow \pi^+\gamma\gamma$	$<1\times10^{-6}$	preliminary
$K \rightarrow \pi^+X,\ X \rightarrow \gamma\gamma$	$<(1\text{-}2)\times10^{-7}$	preliminary
$K \rightarrow \pi^+H,\ H \rightarrow \mu\mu$	$<1.5\times10^{-7}$	published (Ref. 15)
$K \rightarrow \pi^+\mu^+\mu^-$	$<2.3\times10^{-7}$	published (Ref. 15)
$K \rightarrow \mu^+\nu\mu^+\mu^-$	$<4.1\times10^{-7}$	published (Ref. 15)

Although the main objective is the measurement of $K \rightarrow \pi\nu\bar{\nu}$, the detector is very well suited to study many other rare processes: $K \rightarrow \pi\gamma\gamma$, $K^+ \rightarrow \pi^+\mu^+\mu^-$, $K^+ \rightarrow \pi^+e^+e^-$, $\pi^0 \rightarrow \nu\bar{\nu}$, $K^+ \rightarrow \pi^+H$.

A search for the branch $K^+ \rightarrow \pi^+\mu^+\mu^-$ was conducted as part of the 1988 run. In this case, the highly segmented live target and the tracking chamber were mainly used to identify and measure the three charged tracks in the final state. Three events survived the analysis but could not be positively identified as $K^+ \rightarrow \pi^+\mu^+\mu^-$. An upper limit was determined based on 3 background events at the level of 2.3×10^{-7}. Limits were also set on Higgs particle production followed by a decay into $\mu^+\mu^-$ pairs at the level of 1.5×10^{-7} (Ref. 15).

The present experiment will require the significant improvement in intensity to be provided by the new booster being built at the AGS as well as a new beam line. This will increase our kaon stopping flux by one order of magnitude and could then allow us to reach our original goal of exploring the region of the standard model prediction.

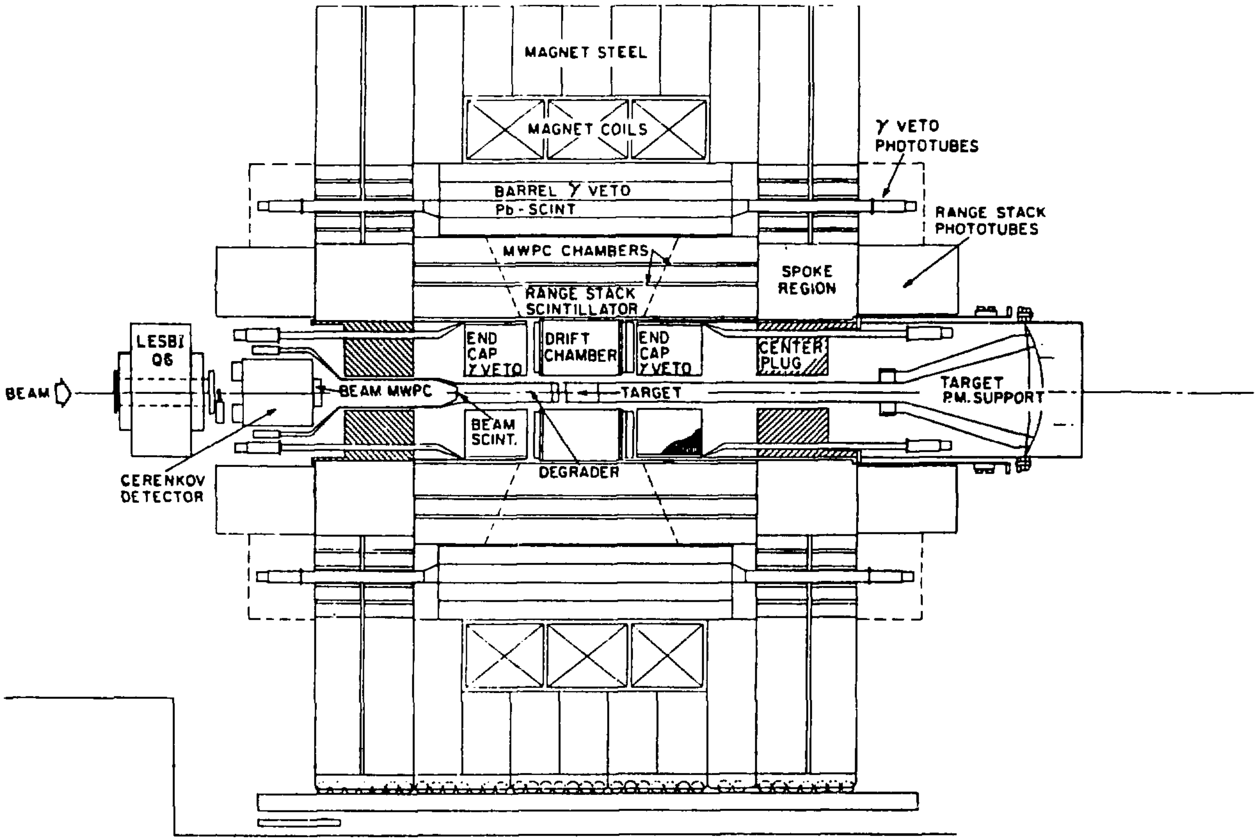

Fig. 10. Schematic side view of the detector.

Further precision testing of the standard model in these processes will require the KAON factory and significant upgrades of our detector.

5. Conclusions

The three meson facilities currently operating have nurtured very interesting activities in the field of particle physics via studies of rare processes. These programs have generated a lot of enthusiasm, in particular amongst the young physicists, and should continue to flourish as higher intensities and novel ideas in detectors are being pursued. The soon to operate Moscow Meson Facilities should have an interesting share of these activities. We wish our Soviet colleagues all the best in joining the club.

References

1. D.A. Bryman, M. Dixit, R. Dubois, J.A. Macdonald, T. Numao, B. Olaniyi, A. Olin and J-M Poutissou, Phys. Rev. D **33**, 1211 (1986).
2. W.J. Marciano and A. Sirlin, Phys. Rev. Lett. **36**, 1425 (1976).
3. D.A. Bryman *et al.*, Phys. Rev. Lett. **50**, 1546 (1983).
4. G. Azuelos *et al.*, Phys. Rev. Lett. **21**, 2241 (1986).
5. D. Britton, thesis University of Victoria 1988 (unpublished).
6. R.N. Mohapatra, in Proceedings, WEIN 89, Montréal (in press).
7. G.A. Beer *et al.*, Phys. Rev. Lett. **57**, 671 (1986).
8. H.J. Mundinger *et al.*, in Proceedings, Rare Decay Symposium, Vancouver (World Scientific, Singapore, 1989), p. 434.
9. H.J. Mundinger and G. zu Pulitz *et al.*, PSI proposal R-89-06.
10. D. Beder and H. Fearing, Phys. Rev. D **35**, 2130 (1986).
11. E.W. Blackmore *et al.*, Nucl. Instrum. Methods **234**, 235 (1985).
12. Y. Kuno, in Proceedings, Rare Decay Symposium, Vancouver (World Scientific, Singapore, 1989), p. 61.
13. M. Selens, Princeton thesis 1988 (unpublished).
14. M.S. Atiya *et al.*, Phys. Rev. Lett. **64**, 21 (1990).
15. M.S. Atiya *et al.*, Phys. Rev. Lett. **63**, 2177 (1989).