Particle Physics with Proton Accelerators

KEK 12 GeV Proton Synchrotron
J-PARC 30 GeV Main Ring

excluding Neutrino physics
Will review ...

* the situation back then
* what people did
* what happened after then
* Flow of experiments
The First Proton Synchrotron

- Low energy than BNL AGS, CERN PS, ...
- Still, the very first machine in Japan that can produce $\pi$, $K$, anti-protons, hyperons, ...
- Physicists worked hard to make beam lines by themselves
Cross section, resonance

E19: \( \pi^- p \rightarrow \pi^0 n \)

E121: \( \pi^- p \rightarrow a_1(1260)n \rightarrow (\pi^+\pi^-\pi^0)n \)

Suzuki et al., NP B294, 961 (1987)

Ando et al., PL B 291, 496 (1992)
Rejected

$\bar{p}p \rightarrow S$-resonance

* E33: anti-protons at the K3 beam line

\[ \Sigma \rightarrow p\gamma \]

\[ \frac{dN}{d \cos \theta_p} \propto 1 + \alpha |P_{\Sigma}| \cos \theta_p \]

- \( \alpha = 0 \) if SU(3)
- \( \alpha \neq 0 \) if QCD
- \( K^- p \rightarrow \Sigma^+ \pi^- \) in bubble chamber

@CERN PS

Manz et al., PL 96B, 217 (1980)
KEK E92

* \( \pi^+ p \rightarrow K^+ \Sigma^+, \ \Sigma^+ \rightarrow p\gamma \)

* \( \Sigma^+ \) polarization \( \sim 98\% \)

* 190 events

Kobayashi et al., PRL 59, 868 (1987)
**FNAL E761**

\[ \Sigma^+ \rightarrow p \gamma \text{ asym} \]

- **800 GeV proton on target**
- **\( \Sigma^+ \)** polarized by 12%
- **34.5k events**

Foucher et al., PRL 68, 3004 (1992)
\[ K^+ \rightarrow \pi^+ \nu \bar{\nu} \]

* Strangeness-changing pure weak current

\[ K^+ \rightarrow \pi^+ e^+ e^- \] can have both neutral weak and electromagnetic currents
LBL Bevatron

Klems et al., PRD 4, 66 (1971)
Cable et al., PRD 8, 3807 (1973)
**LBL Bevatron**

![Graph showing BR(K⁺ → π⁺ νν)](image)

- **BR < 5.6E-7**

Klems et al., PRD 4, 66 (1971)

Cable et al., PRD 8, 3807 (1973)
* BR < 1.4E-7

Asano et al., PL107B, 159 (1981)
\( BR(K^+ \to \pi^+ \nu \nu) \)

**Energy (MeV)**

**US/Japan collaboration**

\[ BR = 1.73^{+1.15-1.05} \times 10^{-10} \]

based on 7 events

Artamonov et al., PRD 79, 092004 (2009)
The decay in flight of $K^+ \to \pi^+ \nu \nu$ was measured by CERN NA62. The branching ratio is $BR = 1.06 \times 10^{-10}$ based on 20-7 = 13 events.
Heavy neutrino?

\[ K^+ \rightarrow \mu^+ \nu_H \]

\[ \nu_\mu = \sum_i U_{\mu i} \nu_i \]
**KEK E10**

* Experiment for $K^+ \to \pi^+ \nu \bar{\nu}$

* Used muon range

KEK E89

- Magnetic spectrometer to measure the muon momentum
- Veto $K^+ \rightarrow \pi^+\pi^0$ with NaI surrounding the target

KEK E89

\[ \pi^+ \rightarrow \mu^+ \nu \]

Mixing Ratio $|U_{\mu\nu}|^2$

Neutrino Mass $m_{\nu}$ (MeV$/c^2$)
With the cylindrical detector for $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
**ν experiments**

- $p + \text{target} \rightarrow K + X$
- $K^+ \rightarrow \mu^+\nu_H$
- $\nu_H \rightarrow \mu^\pm\pi^\mp, \mu^\pm e^\mp\nu_e, \ldots$

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**FIG. 5.** 90% upper limits on the mixing element $U^2_{2e}$ as a function of heavy neutrino mass using the single-channel approach, considering only the contribution from $K^+\rightarrow e^+\nuHN;N\rightarrow e^+\nuH\piH\nuH$, with the three methods $A$, $B$ and $C$. The limits are compared to the ones of PS191 experiment\[6,7\].

**FIG. 6.** 90% upper limits on the mixing elements $U^2_{2e}$ (top), $U^2_{2\text{uni}}$ (middle), $U^2_{2\tau}$ (bottom) as a function of heavy neutrino mass, obtained with the combined approach. The blue dashed lines correspond to the results of the single-channel approach (method $C$). The blue solid lines are obtained after marginalization over the two other mixing elements. In the top plot, the additional blue dotted line corresponds to the case where profiling is used ($U^2_{2\text{uni}} = U^2_{2\tau} = 0$), as explained in the main text. The limits are compared to the ones of other experiments: PS191\[6,7\], E949\[5\], CHARM\[27\].

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Bernardi et al., PLB 203, 332 (1988)
Abe et al., PRD 100, 052006 (2019)
The recent T2K experiments have provided new limits on the mixing element $|U_{\mu\nu}|^2$. The limits are shown as a function of the heavy neutrino mass $M_N$ in the top panel of the figure. The blue solid lines represent the limits after marginalization over other parameters, while the dashed lines show the limits without marginalization. The limits are compared with previous experiments such as K2K, E949, and CHARM.

The lower panel of the figure shows the mixing parameter $U_{\mu\nu}$ as a function of $M_N$. The blue solid line represents the T2K limits, the blue dashed line shows the single-channel result, and the red and orange lines correspond to the 2-body and 3-body PS191 results, respectively. The green dashed line represents the E949 limits.

The KEK E89 experiment has also contributed to the determination of the mixing angles, as indicated in the upper left corner of the figure.
KEK E89 triggered experiment series for ...

- right-handed $\nu$
- T-violation
Right-handed $\nu$?

- Longitudinal polarization of muon
  - $P_\mu = -1$

- Diluted by $P_\mu = +1$ due to right-handed $\nu$?

$\mu^+ \rightarrow K^+ \rightarrow \nu_L$

$\mu^+ \rightarrow K^+ \rightarrow \nu_R$
**KEK E195**

\[ K^+ \rightarrow \mu \nu, \mu \text{ polarization} \]

- Stop \( K^+ \) from \( K\mu2 \) decays in the target

**Graphs:**
- **Cutts et al., PRD 134, 1380 (1969)**
- **Aoki et al., PRD 50, 69 (1994)**
\( T \) violation in \( K^+ \rightarrow \pi^0 \mu^+ \nu \)?

* If transverse muon polarization \( \vec{\sigma}_\mu \neq 0 \), \( T \) violation

\[
\vec{\sigma}_\mu \cdot (\vec{p}_\pi \times \vec{p}_\mu)
\]

\[
= -\vec{\sigma}_\mu \cdot ((-\vec{p}_\pi) \times (-\vec{p}_\mu))
\]
**K⁺ decay in flight**

![Diagram of a particle decay setup with labeled counters, polarimeter, and magnets.](Image)

M. Campbell et al., PRL 47, 1032 (1981)
Large acceptance spectrometer

* for hyper-nucl., $v_H$, $K^+$, ...

Yamazaki et al., IL Nuov. 102, 695 (1989)
These results are summarized in Table I. The CsI(Tl) barrel had 12 holes to admit charged particles, time-of-flight counters, and a muon polarimeter. The setup is noteworthy that the analysis by the previous method may constrain the lightest Higgs boson mass and/or other light Higgs bosons.

In conclusion, we obtained the values of $\Delta \text{Im}(\xi)$ for different years, shown in the graph. The present experiment was performed using a toroidal magnet with 12 gaps. The setup is shown in the figure.

A distinct feature of the present experiment was the high decay kinematic resolution, thus the photon calorimeter was used to identify photons. This work was supported in Japan by a Grant-in-Aid from the Ministry of Education, Science, Sports and Culture, and by JSPS; in Russia by the Ministry of Culture, and by NSF and DOE. The authors thank K. Nakai, K. Shim, and other colleagues.

The setup is shown in the figure, with the CsI(Tl) barrel, time-of-flight counters, and a muon polarimeter. The CsI(Tl) barrel had 12 holes to admit charged particles, time-of-flight counters, and a muon polarimeter. The setup is noteworthy that the analysis by the previous method may constrain the lightest Higgs boson mass and/or other light Higgs bosons.
Lepton Number Violation

$K_L \rightarrow \mu e$
BNL E780 w/ 24 GeV p

Schaffner et al., PRD 39, 990 (1989)
KEK E137

* Double-arm, double magnet spectrometer

Akagi et al., PRL 67, 2614 (1991)
BRL E791

Arisaka et al., PRL 70, 1079 (1993)
BNL E871

* 24 GeV protons, 1.5E13 ppp
* “Beam stop” to reduce rates downstream

Belz et al., NIMA 428, 239 (1999)
Ambrose et al., PRL 81, 5734 (1998)
$K_L \rightarrow \mu \mu$
Argonne ZGS
12 GeV/c p

* Double spectrometers
* 15.4 events

Schochet et al., PRD 19, 1965 (1979)
The analysis began with a pattern recognition algorithm for a global fit of each track, incorporating multiple-criteria. To extrapolate the number of contamination was greatly reduced by using PBG and track 3-momenta. The first fitter (FT) minimized the error, giving an uncertainty on the background, which was subtracted by using PBG and track 3-momenta. The fitter (FT) minimized the error, giving an uncertainty on the background, which was subtracted by using PBG and track 3-momenta. There was also an uncertainty on the background, which was subtracted by using PBG and track 3-momenta. The analysis began with a pattern recognition algorithm for a global fit of each track, incorporating multiple-criteria. The fitter (FT) minimized the error, giving an uncertainty on the background, which was subtracted by using PBG and track 3-momenta.

KEK E137
- 177.8 events
  Akagi et al., PRD 51, 2061 (1995)

BNL E791
- 706.2 events
  Heinson et al., PRD 51, 985 (1995)

BNL E871
- 6.2k events
  Ambrose et al., PRD 84, 1389 (2000)
New Physics

\[
W^- \rightarrow t + \bar{W}^-
\]

\[
Z^0 \rightarrow \nu + \bar{\nu}
\]

Standard Model

\[
\text{SM background is small (BR~3E-11)}
\]

\[
\text{small (BR~3E-11)}
\]

\[
\text{well known (~2\% theo. error)}
\]
$BR(K_L \to \pi^0 \nu \nu)$

$\pi^0 \to \gamma \gamma$

$\pi^0 \to e^+ e^-$

PLB 447, 240 (1999)

PRD 61, 072006 (2000)
The acceptance loss was supported by the fact that the distance, the single event sensitivity for $K$ photons was estimated separately by using real data and photon cluster and on the timing difference between two $(6.4\%)$ were major contributions. For Run-2, the accidental $\approx 1$ was set to be $\approx 2$.

The acceptance loss due to accidental activities in the activity in the CV and in some other photon counters. Run in 2005. In this analysis, we used the data in the second run of $\approx 2$.

Photons to the BA were identified by the $C$ component for detecting extra photons and rejecting those candidates events. There were two types of background events. One was the decays and the other was the events due to neutrons'').

FIG. 1 (color online). Schematic cross-sectional view of the E391a detector. ''0m'' in the scale corresponds to the entrance of the beam at the downstream end. BA consisted of a series of counters. In order to achieve high efficiency of particle detection, we masked the signal box so that all the selection components for detecting extra photons and rejecting those candidate events (signal box) in the $Z_{\text{vtx}}$ (cm) region was separated by a thin multilayer film ("membrane") and four 6-mm-thick scintillator plates that were filled the volume between the beam hole and the innermost hodoscope that was placed 50 cm upstream of the calorimeter and without any in-time hits in the other counters. The systematic uncertainty of the single event sensitivity and background estimates due to halo neutrons in particular, systematic uncertainties of the single event sensitivity were reproduced.

FIG. 27. Scatter plot of $P_T$ (GeV/c) vs. $Z_{\text{vtx}}$ (cm) for Run-3 case, where the errors are dominated by uncertainty in $P_T$. An upper limit for the branching ratio $\approx 2$ was set to be $\approx 2$. $\approx 2$ for Run-3. $\approx 2$ was set to be $\approx 2$.

$T_0$ $(\text{GeV/c})$ $\approx 2$ $\approx 2$. First, we identified clusters in the calorimeter and without the cut, for the data and MC simulations, the differences in quadrature, weighted by the effectiveness of acceptance of the normalization modes, the acceptance of $\approx 2$ was set to be $\approx 2$.
J-PARC in Japan

30 GeV, 100 kW
J-PARC KOTO

Many new detectors for the high intensity

PRL 126, 121801 (2021), PRL 122, 021802 (2019)
KOTO Step 1

2 months/year

\[ \text{BR}(K_L \rightarrow \pi^0 + \nu\bar{\nu}) \times 10^{11} \]

\[ \begin{array}{c}
0.5 \\
1.0 \\
1.5 \\
2.0 \\
2.5 \\
3.0 \\
3.5 \\
4.0 \\
4.5 \\
5.0 \\
5.5 \\
6.0 \\
6.5 \\
7.0 \\
7.5 \\
8.0 \\
8.5 \\
9.0 \\
9.5 \\
10.0 \\
10.5 \\
11.0 \\
11.5 \\
12.0 \\
\end{array} \]

\[ \begin{array}{c}
2015 \\
2017 (75) \\
2018 \\
2020 \\
2022 \\
2024 \\
2026 \\
2028 \\
\end{array} \]

Grossman-Nir Limit by 4-Gen. 

MSSM-A_U

Excluded by Grossman & Nir

http://www.lnf.infn.it/wg/vus/
J-PARC muon g-2

H-line extension bldg.

- Muon g-2/EDM experiment at J-PARC
- Muon storage magnet
- Muon cooling
- Muon LINAC
- Injection BT
- Muon storage magnet

- $\mu^+ (4 \text{ MeV})$
- $\mu^+ (25 \text{ meV})$
- $\mu^+ (210 \text{ MeV})$
- 0.66 m
$\mu^+ \rightarrow e^+$

J-PARC COMET to search for $\mu$ to $e$ conversion

under construction
Summary

* There were competitive experiments
* KEK 12 GeV PS was a training ground for people to work on Tristan and foreign experiments
* Looking for discoveries at J-PARC
* Hoping for more beam lines and beam time at J-PARC for young people to try their ideas