Analysis of the KARMEN time–anomaly

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The neutrino experiment KARMEN is observing an anomaly in the time distributions of neutral and charged current events on 12C induced by neutrinos from the π+-µ+-decay chain at rest [1]. In this contribution we present an analysis of the time anomaly based on data recorded from 1990-98. The hypothesis that a slowly moving massive and weakly interacting particle X produced in a rare decay branch π+ → µ+ + X is the source of the phenomenon leads to a statistical significant and self consistent description of the experimental observation.

1. Introduction

The neutrino experiment KARMEN at the ISIS spallation neutron facility at the Rutherford Appleton Laboratory investigates neutral current (NC) and charged current (CC) neutrino interactions on 12C using neutrinos νµ, νe and νµ from the π+-µ+-decay chain at rest. Due to a very low background level of cosmic induced events and beam correlated low energetic neutrinos KARMEN is also capable of a search for ν-flavour oscillations in the appearance channel ¯νµ → ¯νe [8] with high sensitivity. The unique features of ISIS are the time structure of the proton beam and the corresponding ν-pulses. The ISIS synchrotron generates proton pulses of 800 MeV with 200 μA average beam current which are extracted with a repetition rate of 50 Hz. Each pulse consists of two proton bunches each with a base width of 100 ns separated in time by 330 ns. Due to the short life time of the π+ (τ = 26 ns) a prompt burst of νµ is emitted in the first 0.5 μs after beam on target. Later in the time window from 0.6-10.6 μs only νe and ¯νµ from the much slower µ+-decay (τ = 2.2 μs) are expected to emerge from the source.

The KARMEN detector is a 56 ton high resolution, liquid scintillation calorimeter located at a mean distance from the proton beam stop of 17.7 m. The excellent detector performance is briefly described by the resolutions in energy ΔE/E = 11.5%/√E[MeV], in space Δx, Δy, Δz < 15 cm and in time Δt < 2 ns. To shield the central detector against cosmic radiation and beam correlated high energy neutrons the whole system is enclosed in three layers of veto counters and placed inside a massive blockhouse of 7000 t of steel. The third layer of 300 m² active plastic scintillator was installed inside the steel walls of the blockhouse in 1996. Due to this veto upgrade neutrino nuclei interactions are now measured almost background free [2,7].

2. Anomaly in the time distribution

In the window of 0.6-10.6 μs after beam on target the contribution of neutrino induced reactions Nν is expected to reflect the 2.2 μs life time of the muons decaying in the target. Cosmic induced background NC,B is expected to be flat in time. The definition of the null hypothesis H0: Nν=Nν+Nc,B can be used to separate this two components with a maximum likelihood method (ML). Figure 1 (a) shows the time distribution of all neutrino like events with energies from 10-35 MeV in the time window 0.6-10.6 μs. The fit result (solid histogram) is superimposed to the data points. Apart from the fact that the data describe the expectation very well there is a visible excess of events in the shaded region between 3.1-4.1 μs. Figure 1 (b) shows the time distribution after subtracting the ML-fit from the data. The excess can be summarized in the following event numbers:

N_{meas}(3.1 - 4.1μs) = 658 events
N_{fit}(3.1 - 4.1μs) = 555 ± 6.1 events.
The number of excess events is given by

$$d = \frac{N_{\text{meas}} - N_{\text{fit}}}{\sqrt{N_{\text{meas}} + \sigma^2_{N_{\text{fit}}}}} = 4.23 \sigma.$$  

The probability to measure more than 658 events between 3.1-4.1 μs is therefore

$$P_{3.1-4.1\mu s}(N \geq 658) = 0.00117 \%.$$  

The number of excess events is given by

$$N_X = (N_{\text{meas}} - N_{\text{fit}}) \pm \sqrt{N^2_{\text{meas}} + N^2_{\text{fit}}} \quad (1)$$  

$$\Rightarrow N_X = 103 \pm 34 \text{ events} \quad (68 \% \text{ C.I.}).$$  

Statistical goodness of fit tests based on maximum likelihood and Kolmogorov–Smirnov tests result in confidence levels less than 1% for $H_0$. This is a hint that there is a distinct distortion in the data [2]. Any attempt to explain this peak like structure by systematic effects failed; e.g. beam associated background from high energy neutrons, errors in electronics and data acquisition or after pulses from the proton beam are ruled out. Besides a statistical fluctuation only an explanation in terms of new physics seems to be left to explain the anomaly.

### 3. Hypothesis tests

Every particle hypothesis $H_1$ which may explain the time anomaly has to fulfill certain very strict boundary conditions imposed by the observations. These boundary conditions are the observed base width of approximately 1 μs of the distortion (see fig. 1) and the observed energies of anomaly events between 10-36 MeV. The third very important boundary condition is that an X-particle must be very slow to appear at a mean value $\bar{t}$ of event times approximately 3.6 μs after beam on target. Taking the effective target distance $d$ of the KARMEN central detector of 17.56 m into account we calculate the particle velocity to

$$\nu_X = \frac{d}{\bar{t}} \simeq 0.5 \text{ cm/ns} \Rightarrow \beta_X \simeq \frac{1}{60}. \quad (2)$$

There is only a single hypothesis which does fulfill the mentioned boundary conditions without any contradictions throughout the analysis: There is a very rare branch of the decay of positive pions at rest

$$\pi^+ \rightarrow \mu^+ + X \quad (3)$$

in a muon and a X-particle. Since the X-particle slowly penetrates the heavy shielding of 7 m it must be massive, neutral and only weakly interacting. The rest mass of the X-particle is nearly the mass difference between the pion and the muon which is known very precisely

$$m_{\pi^+} - m_{\mu^+} = 33.91157 \text{ MeV/c}^2 \pm 0.67 \text{ keV/c}^2. \quad (4)$$

As this particle must have a velocity of $\beta_X \simeq \frac{1}{60}$ the kinetic energy is approx. 5 keV, i.e. the phase space available for the decay. The signal in the scintillator is induced by the decay of the X-particle in particles like lepton pairs or photons and neutrinos. Examples for such decays are $X \rightarrow e^+e^-\nu$ or $X \rightarrow \nu$ which are assumed to be the main branches for the decay of massive neutrinos like the X-particle [3,4]. This hypothesis describes the observed energies and the particle velocity. The base width of the distortion of a X-particle in the time distribution is calculated with Monte Carlo simulations taking into account the
ISIS double pulse structure of protons, the particle velocity and the extensive KARMEN-detector geometry. This calculation results in an expected width of the anomaly of 1.2 μs at β = 1/60 which is in remarkably good agreement with the observation (see figure 1).

4. Likelihood analysis in x and t, ToF-correlation of an X-particle

With a velocity of 0.5 cm/ns the traveling time of an X-particle in the central detector along the 3.5 m long module axes is approximately Δt_{travel} = 700 ns. With a time resolution of less then Δt < 2 ns and a spatial resolution of Δx, Δy, Δz < 15 cm there must be a unique time of flight correlation (ToF) of each X-particle decay between the two coordinates t and x. A ToF correlation would be a strong argument against systematic or electronic effects.

To test the x-t-correlation a ‘raster scan’ ML-method is used. The 2-dimensional probability density functions (p.d.f.’s) for the X-particle are calculated with Monte Carlo methods. The p.d.f.’s for neutrinos are known analytically whereas the cosmic background is measured with high precision. To apply a raster scan method the p.d.f.’s are calculated for velocities from 0.3 - 0.8 cm/ns in steps of 0.001 cm/ns. Figure (2) shows the experimental likelihood function and the corresponding estimates for the number of X-particles. To compare the ML result with the expectation given an X-particle the functions obtained with high statistics are normalized to the experimental result and plotted in the same figures as dotted lines. The shape of the function of expected peak events fits perfectly as well. The result of the ML analysis yields

\[ V_{X}^{\min} = 0.487 \pm 0.004 \text{ cm/ns} \quad (68\% \text{ C.I.}) \]
\[ N_{X}^{\min} = 69 \pm 27 \text{ events} \quad (68\% \text{ C.I.}) \]
\[ \Delta L_{\min} = 9.16 \text{ log. units.} \]

1 both of them measured and calibrated independently.
2 The pathology of the L-function is explained in [2].

Figure 2. Likelihood function (a) and number of fitted X-particles (b) as a function of hypothetical particle velocities. The solid line shows the experimental result. The dotted line does correspond to a high statistics data set scaled down to the experimental values.

To obtain the correct statistical interpretation (in the frequentist approach) of this result Monte Carlo generated data sets from the space of \( H_0 \) with experimental event statistics have to be investigated. Figure (3) shows the distributions of the likelihood ratio \( \Delta L_{\min} \) (a) and the number of estimated X-particles (b) resulting from 10000 MC data sets with \( N_X = 0 \) events. The solid vertical line indicate the experimental results in both distributions. The region under the distributions to the right of the lines are the critical regions. Taking \( \Delta L_{\min} \) as the test statistic the critical region is

\[ P(\Delta L_{\min}^{MC} \geq \Delta L_{\min}^{exp}) = 0.1\%. \quad (5) \]

Restricting the analysis to positive fluctuations only, the confidence level for \( H_0 \) shrinks to

\[ P_{\text{positive}}(\Delta L_{\min}^{MC} \geq \Delta L_{\min}^{exp}) = 0.03\%. \quad (6) \]
Figures 3. Distribution of the likelihood ratio (a) and number of fitted X-particles (b) from 10000 $H_0$ KARMEN data sets analyzed under the hypothesis $H_1$.

Taking $N_X$ as the test statistic (figure 3 (b)) there is only one experiment in 10000 which has more than 69 events.

5. Energy distribution of the X

Applying the ToF analysis on independent data sets with energy windows of e.g. 5 MeV bins we get the energy distribution of X-particles. In each data set the ML-fit should give an estimate of the according number of ToF-correlated X-particles inside a narrow interval around the correct velocity of $V_X = 0.487 \text{cm/ns}$. The resulting energy spectrum is shown in figure (4). There is no hint of excess events above 35 MeV. Assuming other X-particle hypotheses like the decay $\mu^+ \rightarrow e^+ + X$, X-particles should have a mass of more than 100 MeV and therefore deposit more than 35 MeV in the detector. For further information on theories and experimental investigations of different hypothesis references [3–6] are recommended. The upper bound in observed energies fits very nicely to the investigated scenario of the $\pi^+ \rightarrow \mu^+ + X$ decay.

Figure 4. Energy distribution of events with ToF-correlation estimated in independent data sets (in 5 MeV bins) with the ML analyses at the particle velocity of $V_X = 0.487 \text{cm/ns}$.

Under the assumption of a pure three body decay of the X-particle in lepton pairs and a neutrino $X \rightarrow e^+e^-\nu$, an energy distribution similar to the one superimposed in figure (4) as a solid curve is expected [3]. Below 10 MeV an analysis is not possible due to high background level and slow neutrons from the accelerator. If the X-particle should decay via a radiative decay $X \rightarrow \gamma\nu$ only a narrow line at 17 MeV would be expected. This can certainly be excluded.

REFERENCES
8. T.E. Jannakos, these proceedings.