Title

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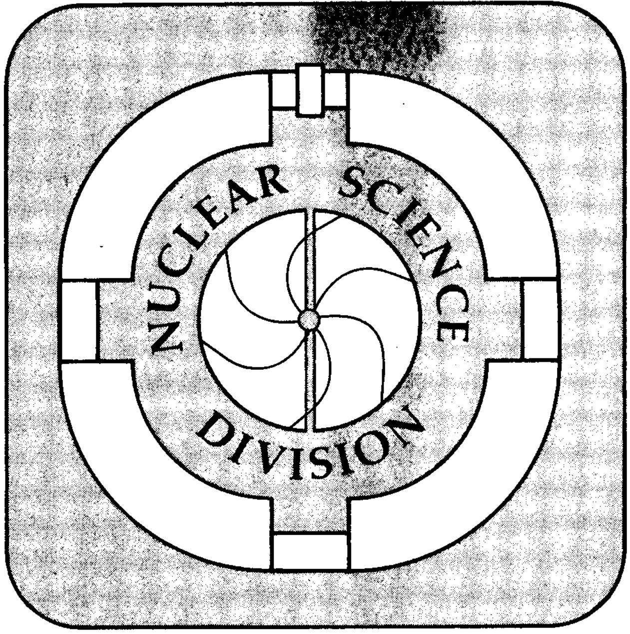

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Measuring the Muon Neutrino Mass with Binary Pulsars*

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The large proton decay experiments have been successful in pushing the limit of the proton lifetime back to beyond 10^{31} years. They are also the first detectors to be sensitive to the kinematics of neutrino interactions and so may make the first neutrino telescopes. Recently, in fact, one group may have observed Cygnus X3 as a strong muon neutrino source. This possibility is based on the observation of 18 neutrino events which share two interesting features;

1) They all can be mapped to within a three degree cone about Cygnus X3 and

2) They arrive at times consistent with the duty cycle of Cygnus X3 (period 4.8 hours with a duty cycle of 60%).

The prospect of observing strong pulsed sources of muon neutrinos far away from the earth opens up the possibility of measuring the muon neutrino mass far more accurately than presently possible by any terrestrial method.

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If neutrinos have mass then their velocity will be slightly less than c, and so they will arrive on the earth lagging the photons that were produced at the same time from the same source. The distance to binary pulsars is so vast (typically tens of kiloparsecs) that particles with v/c on order of $(1 - 10^{-9})$ will have lag times ranging from minutes to hours. By measuring the lag time and the neutrino momentum, one can determine the neutrino mass.

In addition to being so far away, binary pulsars are potentially useful for four other reasons;

1) They release their energy towards the earth in bursts with duty cycles typically on order of 50%.
2) They typically have long (on order of hours) periods.
3) The photon intensity vs. time is usually very consistent between periods.
4) Some pulsars may be strong sources of muon neutrinos as suggested by recent measurement.

One may show;

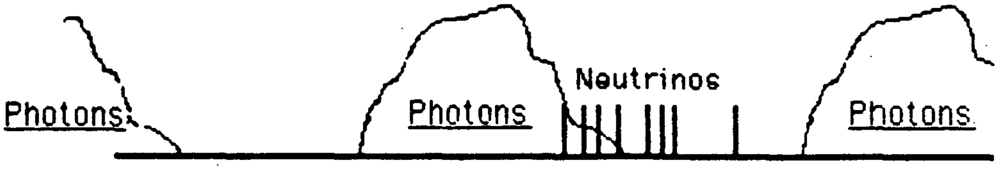
$$v/c = \frac{1}{(1 + tc/d)} \simeq 1 - tc/d$$

for t (lag time) on order of hours and d (distance to source) on order of kiloparsecs. If one then measures the momentum of the neutrino, the mass is given by;

$$M = ((P/c)\,[1 - (v/c)^2]^{1/2})/(v/c) \simeq (P/c)\,(2tc/d)^{1/2}$$

Using Cygnus X3 as an example, d = 10 kiloparsecs, let t = 4.8 hours (one period) and suppose the momentum of the neutrino was measured to be 1 Gev/c, the corresponding neutrino mass would be 180 kev/c^2 . (The present limit is 500 kev/c^2.)

If the duty cycle of the pulsar was very small, (say 1%) then the determination of the lag time would be very straight forward. Unfortunately, the duty cycles of binary pulsars are often on order of 50%, and so measuring the mass is somewhat more difficult. Below is a picture of what a data set may look like. (Neutrino events selected by requiring the neutrino momentum projects back to the suspected source. All neutrino events are condensed on one period).



At first, one might think to measure the time difference between the mean of the photon and neutrino distribution. This will not work for two reasons. First, the event rate is very small. Second, the two distributions will not have the same shape since the neutrinos will have some unknown momentum distribution.

A better way to determine the neutrino mass is as follows. Assume that the neutrino intensity vs. time is similar to the photon intensity. Then the probability that a given neutrino was produced at a given time is proportional to the photon intensity at that time. So for a given arrival time, one may bin the possible start times, each one corresponding to a different possible mass for the momentum of the observed neutrino. Each possible mass may be weighted by the probability that the neutrino was released at the corresponding time, and the resulting weighted masses histogrammed. The resulting histogram will peak around the neutrino mass.

It may not be necessary to consider the entire period. The part of the period that need be considered starts with the arrival of the neutrino and ends at that advanced time which corresponds to the present experimental limit of the muon neutrino mass. Thus, one is in principle able to improve on any limit set by another experiment by simply renormalizing the probabilities that went into producing the weighted histogram, and then redoing the analysis. If the time over which the signal is a minimum is large enough so that a neutrino that arrives at the start of one period can be certain to not have been produced in the preceding period, then one may be able to place very a severe (tens of kev/c^2 or better) limitation on the muon neutrino mass, if one is fortunate enough to find a neutrino event very close to the beginning of the period.

For Cygnus X3 the signal minimum lasts for 1.9 hours. If a 2 Gev/c neutrino were detected within 5 minutes of the start of the period one could be certain that the neutrino did not come from the preceding period, since that would correspond to a neutrino mass greater than the existing limit. The mass of the muon neutrino would then be constrained to be less that 50 kev/c^2.

There are certain systematic effects that one must consider that may effect the time difference between the photons and neutrinos. They are;

1) The effect of the interstellar gas. The interstellar gas has an index of refraction which is not identically unity. If one assumes that n - 1 is proportional to the density of the gas, it can be shown that this will delay the photons by only 10^{-14} seconds over a distance of ten kiloparsecs.

2) The physical extent of the source. A binary system with periods on order of hours may be about 10^5 kilometers in diameter. Path differences between the photons and neutrinos will produce time delays on order of 1 second over this distance.

3) The effect of the atmosphere of the source. A large index of refraction ($n = 1.5$) of the source atmosphere may delay the photons on the order of seconds.

4) The red shift of massive neutrinos leaving the source. The change in the v/c of a massive neutrino will delay its departure from the source by less than 10^{-10} seconds.

5) There may be another muon neutrino source within angular resolution of the momentum projection.

The largest errors will come from the uncertainty in the distance to the pulsar (typically 50%) and the momentum resolution of the detector (about 20% near 1 Gev/c).

Once the mass of the muon neutrino is known, (assuming that is not identically zero) then one could in principle use the lag time to determine the distance to binary pulsars, and other objects. In particular, if extragalactic supernove are sources of muon neutrinos, this method could establish an independent distance scale to nearby galaxies.

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