Sterile Neutrinos and Pulsar Velocities Revisited

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We calculate the momentum given to a proto neutron star during the first 10 seconds after temperature equilibrium is reached, using recent evidence of sterile neutrinos and a measurement of the mixing angle. This is a continuation of an earlier estimate with a wide range of possible mixing angles. Using the new mixing angle we find that sterile neutrinos can account for the observed pulsar velocities.

PACS Indices:97.60.Bw,97.60.Gb,97.60.JD
Keywords: Supernova, pulsars, pulsar kick, sterile neutrinos

I. INTRODUCTION

It has been observed that many pulsars move with much greater velocities than other stars in our galaxy. This is called the pulsar kick. See Ref.[1] for a review. Since neutrinos produced by the URCA process dominate the emission of energy during the first 10 seconds after the collapse of a heavy star, and for electrons in the lowest Landau level the direction of motion is aligned with the strong magnetic field, it was expected that active neutrino emission would account for the pulsar velocities. It was shown, however, that due to the small mean free path of active neutrinos this does not work[2, 3]. Using the modified URCA process, it was shown that active neutrino emission might account for the observed pulsar velocities during the period of about 10 to 20 seconds, when the surface of the neutrinosphere is at the surface or the proto-neutron star[4].

A few years ago an experiment by the MiniBooNE Collaboration[5] found that the data for electron neutrino appearance showed an excess at low energies, in comparison to what was expected in the standard model. This is consistent with the earlier LSND experiment[6]. An analysis at that time[7] indicated that there are either one or two sterile neutrinos, but only could extract a wide range of mixing angles. Due to the long mean path compared to active neutrinos, this suggests that sterile neutrinos could account for the pulsar kicks. This possibility was confirmed[8], but due to the uncertainty in mixing angle the results could not be compared to observations. Prior to this pulsar kicks from heavier sterile neutrinos, possibly dark matter, was estimated for a range of parameters[9].

Recently the mixing angle in a 3+1 scenerio has been determined with much greater accuracy[10]. Last year there was a new analysis of short- baseline neutrino oscillation data[11] in which a 3+2 scenerio is preferred. In the present work we will make use of the theoretical formulation of Ref[8] with the new mixing angle result[10], calculate the pulsar velocity as a function of temperature, and compare to observations.

II. ASYMMETRIC STERILE NEUTRINO EMISSIVITY AND PULSAR VELOCITIES

Within about 10 seconds after the collapse of a large star about 98% of neutrino emission occurs, with neutrinos produced mainly by URCA processes. Due to the strong magnetic field, neutrino momentum asymmetry is produced within the neutrinosphere if the electron is in the lowest Landau level, but with a small mean free path they are emitted only from a small surface layer of the neutrinosphere, and the pulsar kick cannot be accounted for. If the electron neutrino oscillates to a sterile neutrino, the mean free path is much greater, and pulsar velocities consistent with observation are possible, as found in Ref[8]. To determine the pulsar velocities as a function of pulsar luminosity or temperature, one must know the effective mean free path and the probability, P(0), for the electron to be in the n=0 Landau level. The expression for the asymmetric neutrino emissivity and resulting pulsar momentum and velocity was derived in detail in Ref[8], and we shall therefore only give a brief review. Then the pulsar (neutron star) velocity will be found as a function of temperature.
A. Mixing Angle in Neutrinosphere Matter

With the mixing angle for electron, sterile neutrinos (ν_e, ν_s) in neutrinosphere matter = θ_m, the two neutrino flavors have the form

|ν_1⟩ = cosθ_m|ν_e⟩ − sinθ_m|ν_s⟩
|ν_2⟩ = sinθ_m|ν_e⟩ + cosθ_m|ν_s⟩ .

As was shown in Refs[8, 9], with θ the mixing angle in vacuum, sin^2(2θ_m) ≃ sin^2(2θ), therefore from Ref[10]

sin^2(2θ_m) ≃ 0.15 ± 0.05 .

Note that we used 0.004 ≤ sin^2(2θ_m) ≤ 0.2 in Ref[8]

B. Neutrino Emissivity and Pulsar Momentum With a Strong Magnetic Field

Using the general formulation for neutrino emissivity, see, e.g., Refs[12, 13], the main source of the asymmetric emissivity that produces the pulsar velocity is that the electron has a large probability to be in the lowest (n=0) Landau level, defined as P(0). A detailed derivation of the asymmetric emissivity, ε^AS, is given in Ref[8], with the result

ε^AS ≃ 0.33 × 10^{21} T_9^7 P(0) erg cm^{-3} s^{-1} ,

where T_9 = T/(10^9 K), with T the temperature. In Refs[4, 8] P(0) was derived, with the result that P(0) ≃ 0.4, in agreement with Ref[9]. From this and Eq[8] one finds for the proto neutron star momentum

p_{ns} ≃ V_{eff} 3.3 × 10^{21} T_9^7 erg cm^{-3} ,

where V_{eff} is the effective volume for the emissivity.

C. Estimate of V_{eff} = Effective Volume for Emission

V_{eff}, the volume at the surface of the neutrinosphere from which neutrinos are emitted, is given by the mean free path of the sterile neutrino, λ_s, and the radius of the neutrinosphere[8]:

V_{eff} = (4π/3)(R_{ν}^3 − (R_{ν} − λ_s)^3)
≃ 4π R_{ν}^2 λ_s/\sin^2(2θ) ,

with λ_s = λ/\sin^2(2θ), where λ is the active neutrino mean free path.

D. Neutron Star Speed = v_{ns}(T)

Using p_{ns} = M_{ns} v_{ns} and Eqs[15], with the mass of the neutron star taken as M_{ns} = M_{sun} = 2 × 10^{33} gm, one finds with \sin^2(2θ) = 0.15

v_{ns} ≃ 22.3 × 10^{-7} (T/10^{10} K)^{7/2} km s^{-1} .

During the early stages after the collapse of a massive star temperatures T=20 MeV are expected[9]. With T = 10 to 20 MeV the pulsar velocities, with a 50% range due to the uncertainty in \sin^2(2θ), are shown in Fig. 1. These result can be compared to the pulsar velocity data as a function of luminosity, as shown in Fig. 2.
III. CONCLUSIONS

As can be seen in Fig. 1., pulsar velocities of over 1000 km/s are predicted from sterile neutrino emission with the mixing angle recently measured\cite{10}. Therefore, sterile neutrino emission can account for the large pulsar velocities for high luminosities (large T as in Fig. 1) that have been measured, as shown in Fig. 2. This is a possible explanation of a puzzle that many have tried to explain for decades.

Acknowledgements

This work was supported in part by the DOE contracts W-7405-ENG-36 and DE-FG02-97ER41014, and in part by a grant from the Pittsburgh Foundation. We thank Dr. William Louis for information about recent neutrino oscillation experiments and the measurement of sterile neutrino mixing angles.

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