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Two nucleon (B − L)-conserving reactions involving tau leptons

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ABSTRACT

Tau lepton emission in two-nucleon disappearance reactions from within nuclei which conserve baryon number minus lepton number (B − L) is considered. It is shown that some existing limits on proton decay channels and two-nucleon disappearance reactions resulting in electrons and muons can be applied to $\Delta B = \Delta L = 2$ decays involving τ leptons. For the two-nucleon disappearance channel $np \to \tau^+ \bar{\nu}_\tau$ the estimated limit for the partial mean life is $\frac{\tau}{Br} > 1 \times 10^{30}$ yrs based on results from the IMB3 experiment. Re-analysis of existing data and future experiments could result in higher sensitivity for two-nucleon disappearance modes involving τ lepton final states.

1. Introduction

The search for baryon number (B) violating reactions is motivated by the apparent dominance of matter over anti-matter in the universe. Although predictions for proton decay ($\Delta B = 1$) from Grand Unified Theories have not been confirmed by experiments ruling out the minimal SU(5) scenario, baryon and lepton number violations occur in many extensions of the Standard Model (SM) at potentially observable rates [1]. Theories incorporating new heavy particles and new interactions such as supersymmetry or extra dimensions may also include baryon number violation. In some extensions of the SM the quantity B − L (baryon number minus lepton number (L)) is conserved, so modes like $p \to e^+\pi^0$ with $\Delta B = \Delta L = 1$ are favored.

(B − L)-conserving reactions with $\Delta B = \Delta L = 2$ involving two-nucleon disappearance from within nuclei such as $pp \to e^+e^+$, $pp \to \mu^+\mu^+$, $pp \to e^+\mu^+$, $np \to e^+\bar{\nu}_e$ and $np \to \mu^+\bar{\nu}_\mu$ have been searched for [2]. The Particle Data Group (PDG) [3] lists 13 two-nucleon disappearance partial mean life limits with the longest $\frac{\tau}{Br} > 5.8 \times 10^{30}$ yrs [2][1] due to the channel $pp \to e^+e^+$. The "partial mean life" limits are the limits on $\frac{\tau}{Br_i}$ where τ is the total mean life and Br_i is the branching fraction for the decay mode in question [3]. Processes with $\Delta B = \Delta L = 2$ have been considered in theoretical models which typically involved an extended Higgs sector. For example, Arnellos and Marciano [4] discussed such processes in the context of an SU(5) model containing a Higgs 50-plet. Invisible modes with $\Delta B = \Delta L = 2$, particularly $nn \to \bar{\nu}_l\bar{\nu}_l$ where $l = e, \mu, \tau$, would be severely suppressed by angular momentum conservation but two-nucleon disappearance modes with $\Delta B = 2$ and $\Delta L = 0$ such as $nn \to$ invisible or $nn \to \nu_l\bar{\nu}_l$ have been searched for [5]; the resulting limits would also apply to $nn \to \bar{\nu}_l\bar{\nu}_l$ decays. Recently, theoretical models which do not generate proton decay but involve $\Delta B = 2$ (which results in neutron–anti-neutron oscillations) and $\Delta B = \Delta L = 2$ have been considered by Arnold, Fornal, and Wise [6]. Dimensional analysis indicates that the fundamental scale for suppression of $\Delta B = 2$ processes may be at the few TeV scale [7], much lower than the grand-unification scale suggested by proton decay.

While single nucleon decay to final states involving on-shell τ leptons cannot occur due to energy conservation, $\Delta B = \Delta L = 2$ two-nucleon disappearance reactions within nuclei such as $np \to \tau^+\bar{\nu}_\tau$ and $pp \to \tau^+e^+$ could proceed. Reactions with $\Delta B = \Delta L = 2$ involving τ leptons may possibly be enhanced over direct decays to final states with electrons and muons due to generation-dependent effects or mass-dependent couplings to exotic Higgs particles. For two-nucleon disappearance modes with τ lepton final states, several τ decay channels may be observed including $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$, $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$, $\tau^+ \to \pi^+\bar{\nu}_\tau$, and $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$ with branching ratios of 17.8%, 17.4%, 10.8%, and 25.5%, respectively [3]. B-violating decays with $\Delta B = 1$ such as $p \to \pi^+\bar{\nu}_\tau$ involving τ leptons in virtual intermediate states have also been discussed [1] but the effects were found to be very small.

At present, there are no partial mean life constraints on two-nucleon decays into τ leptons listed in the PDG compilation [3]. However, the limits found by previous proton decay experiments

[1] All limits discussed here will be at 90% c.l.

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may be useful for obtaining first limits on such reactions. In particular, searches for direct decays to electrons, muons, or pions used kinematic constraints which may have overlap with some τ lepton decay channels. For example, the results for $np \to e^+\bar{\nu}_e$, $np \to \mu^+\bar{\nu}_\mu$, $p \to e^+\nu\nu$, and $p \to \mu^+\nu\nu$ may be used to obtain limits on $np \to \tau^+\bar{\nu}_\tau$ in which the τ decays to leptons. Similarly, searches for $pp \to \mu^+e^+$ and $pp \to e^+e^+$ reactions may be examined for applicability to limits on $pp \to \tau^+e^+$ and the results for $pn \to \pi^+\pi^0$ searches may be considered to limit the mode $np \to \tau^+\bar{\nu}_\tau$ in which the τ lepton decay $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$ occurs. Limits obtained on single proton decay $p \to \pi^+\nu$ and $p \to \rho\nu$ may also be considered for application to searches for $np \to \tau^+\bar{\nu}_\tau$ followed by $\tau^+ \to \pi^+\bar{\nu}_\tau$ and $\tau^+ \to \pi^+\pi^0\bar{\nu}_\tau$. In the following, the results from several experiments will be examined to determine their applicability for setting limits on the partial mean life for the reaction $np \to \tau^+\bar{\nu}_\tau$.

2. Experimental limits on $np \to \tau^+\bar{\nu}_\tau$

The Frejus experiment [2] with target material of Fe provided limits on many two-nucleon disappearance modes. In this experiment, a minimum energy threshold of 200 MeV for triggering was applied and the energy resolution was quoted as $\sigma_E = \frac{\Delta E^{em}}{E} = 15\%$ (12%) at 400 (1000) MeV for electromagnetic showers due to electrons or gamma rays [2]. For muons at 300 MeV/c traveling perpendicular to the iron plates the momentum resolution was 3% (or 10 MeV/c) [2]. Accepted events were required to be consistent with kinematic expectations such as energy conservation. For example, considering the disappearance of a neutron and proton from ^{56}Fe, the mass difference between the ground states of ^{56}Fe and ^{54}Mn [8] results in 1858 MeV available energy for the decay products. Using the τ lepton mass $m_\tau = 1776.82 \pm 0.16$ MeV/c^2 [3], the final state leptons in two-nucleon disappearance reactions $np \to \tau^+\bar{\nu}_\tau$ from ^{56}Fe would each have momentum approximately $P = 79$ MeV/c. In the following, the effects of the small kinetic energy of the τ lepton ($T = 1.8$ MeV) will be neglected.

For τ lepton decays at rest to electrons and muons, $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ and $\tau^+ \to \mu^+\nu_e\bar{\nu}_\tau$, the momentum distribution of the charged lepton decay products follows the "Michel" spectrum [9], originally used to describe muon decays. For $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ ($\tau^+ \to \mu^+\nu_e\bar{\nu}_\tau$) the maximum electron (muon) momentum occurs at approximately $P_{e(\mu)} = 888$ (885) MeV/c. In order to find limits on $np \to \tau^+\bar{\nu}_\tau$ reactions using previous results obtained with e^+ or μ^+ decay products, the fraction of the $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ and $\tau^+ \to \mu^+\nu_e\bar{\nu}_\tau$ charged lepton decay distributions accepted by the kinematic regions used by the experiments needs to be estimated. For example, in the Frejus evaluation of $n \to \pi^0\nu$, an energy acceptance window of about $\pm 3\sigma_E$ relative to the expected visible energy was employed. For the cases $np \to e^+\bar{\nu}_e$ and $np \to \mu^+\bar{\nu}_\mu$ comparable visible energy acceptance windows would be approximately 595–1263 MeV and 717–936 MeV, respectively. For these energy windows approximately $\epsilon_e = 60\%$ of $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ decays and $\epsilon_\mu = 18\%$ of $\tau^+ \to \mu^+\nu_e\bar{\nu}_\tau$ decays would have been accepted.

Limits on the partial mean life of the decay $np \to \tau^+\bar{\nu}_\tau$ can then be roughly evaluated based on the Frejus limits on the reactions $np \to e^+\bar{\nu}_e$, $\frac{\tau}{Br} > 2.8 \times 10^{30}$ yrs, and $np \to \mu^+\bar{\nu}_\mu$, $\frac{\tau}{Br} > 1.6 \times 10^{30}$ yrs [2]. Using the $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ and $\tau^+ \to \mu^+\nu_e\bar{\nu}_\tau$ branching fractions and the acceptance fractions ϵ_e and ϵ_μ results in estimated limits for $np \to \tau^+\bar{\nu}_\tau$ reactions $\frac{\tau}{Br} > 0.3 \times 10^{30}$ yrs and $\frac{\tau}{Br} > 0.05 \times 10^{30}$ yrs.

The Frejus experiment also produced the best limit on $p \to \mu^+\nu\nu$ decay, $\frac{\tau}{Br} > 2.1 \times 10^{31}$ yrs. Here the maximum visible energy would be about 365 MeV. Using a $\pm 3\sigma_E$ energy window results in an acceptance fraction of $\epsilon_\mu = 11\%$ for $\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$ decays and an estimated lower limit on the partial mean life for the reaction $np \to \tau^+\bar{\nu}_\tau$, $\frac{\tau}{Br} > 0.4 \times 10^{30}$ yrs.

Table 1
Summary of results for the limits on the partial mean life $\frac{\tau}{Br}$ of two-nucleon disappearance in the reaction $np \to \tau^+\bar{\nu}_\tau$. The first column indicates the original reaction searched for in the experiment referenced in the second column. The third column shows the τ lepton decay channel used in the analysis.

Decay channel	Experiment	τ decay	$\frac{\tau}{Br}$ [yrs] for $np \to \tau^+\bar{\nu}_\tau$
$np \to e^+\nu_e$	Frejus [2]	$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$	$> 0.3 \times 10^{30}$
$np \to \mu^+\nu_\mu$	Frejus [2]	$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$	$> 0.05 \times 10^{30}$
$p \to \mu^+\nu\nu$	Frejus [2]	$\tau^+ \to \mu^+\nu_\mu\bar{\nu}_\tau$	$> 0.4 \times 10^{30}$
$p \to e^+\nu\nu$	IMB3 [10]	$\tau^+ \to e^+\nu_e\bar{\nu}_\tau$	$> 1 \times 10^{30}$

The IMB3 experiment [10] gave the best limit on $p \to e^+\nu\nu$ decay, $\frac{\tau}{Br} > 17 \times 10^{30}$ yrs, which can be used to evaluate the process $np \to \tau^+\bar{\nu}_\tau$ followed by $\tau \to e^+\nu_e\bar{\nu}_\tau$. IMB3 used energy conservation and anisotropy selection criteria to identify events compatible with the $p \to e^+\nu\nu$ decay signature. The anisotropy of an event was a measure of the net momentum. For $p \to e^+\nu\nu$ decay the anisotropy criterion was chosen to accept single particle emission which would have been consistent with $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ decay. The energy region used to search for $p \to e^+\nu\nu$ [11] was approximately 100–550 MeV resulting in an acceptance fraction for $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ decays of $\epsilon_e = 32\%$. The estimated limit on the partial mean life for $np \to \tau^+\bar{\nu}_\tau$ is then $\frac{\tau}{Br} > 1 \times 10^{30}$ yrs.

Several other experimental results were considered for evaluating two-nucleon disappearance reactions $np \to \tau^+\bar{\nu}_\tau$ and $pp \to \tau^+e^+$ using various τ decay channels. These include the Soudan 2 limit on $p \to \pi^+\nu$ decay [12] using $\tau \to \pi^+\bar{\nu}_\tau$, the IMB3 limit on $p \to \rho^+\nu$ decay [10] using $\tau^+ \to \rho^+\bar{\nu}_\tau$, the Frejus limit on $pp \to e^+e^+$ decay [2] using $\tau^+ \to e^+\nu_e\bar{\nu}_\tau$ and the Super-Kamiokande experiment result on $p \to \pi^+\bar{\nu}$ [13]. However, it appears that the selection criteria used to obtain these results, principally, the allowed energy regions, would have had little overlap with the kinematics of the decay products of the relevant τ decays. Limits on $nn \to \tau^\pm e^\mp$ were also considered using results obtained by IMB3 [11] on $n \to e^+e^-\nu$ and $n \to \mu^+e^-\nu$; however, due to the low momentum of the electron or positron from the reactions $nn \to \tau^\pm e^\mp$, the experimental anisotropy regions selected [11] would have had minimal overlap.

3. Summary

Table 1 shows the lower limit estimates for the partial mean life of the $\Delta B = \Delta L = 2$ process $np \to \tau^+\bar{\nu}_\tau$ obtained by examining previous results of several nucleon decay experiments. The largest lower limit found on the partial mean life was $\frac{\tau}{Br} > 1 \times 10^{30}$ yrs, based on the IMB3 experimental result for $p \to e^+\nu\nu$ [10]. These results also apply to the (B + L)-conserving process $np \to \tau^+\nu_\tau$. Re-analysis of data from Frejus, IMB3, Soudan 2 and other nucleon decay experiments would likely result in considerably greater sensitivity on two-nucleon disappearance reactions resulting in τ leptons. Future and current nucleon decay experiments would be enhanced by explicitly triggering on and considering such channels. In particular, a major advance in sensitivity to two-nucleon disappearance channels involving τ leptons could come from analysis of data from the Super-Kamiokande experiment which might reach partial mean lives of 10^{33} yrs or more [13].

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