Abstract

- Unification of couplings and matter hint at a GUT underlying the SM [1][2]
- With energies of order $\sim 10^{16}$ GeV, Grand Unification is unreachable at accelerators
- Baryon number violating nucleon decay is a definitive prediction and a unique test of GUT models that can be explored in a non-accelerator setting
- Simplest unification based on minimal SU(5) is ruled out by nucleon decay limits [3][4][5], with minimal SUSY extensions strongly limited [6]
- Consider other scenarios as well as higher symmetry groups
- Of interest is SO(10) $\rightarrow$ SU(4) $\times$ SU(2) $\times$ SU(2) $\rightarrow$ SM chain via Pati-Salam [7] model
- With L-R symmetry, Pati-Salam can lead to interesting decay modes such as $|\Delta B-L|=2$ violating decays $p \rightarrow e\nu$ and $p \rightarrow \mu \nu$ (also $|\Delta B-L|$ conserving modes)
- Historically, $p \rightarrow e\nu$ has been proposed to explain "neutrino anomaly" [8]
- This analysis will provide results for the first 3-body nucleon decay search of SK via decay modes of $p \rightarrow e\nu$ and $p \rightarrow \mu \nu$ which may dominate over the typical modes, in some models [9]

Analysis Spectrum & Fitting Results

- Flat phase space is used for signal simulation, an approach validated by comparing charged lepton spectrum approximation [13] based on $p \rightarrow e\nu$ formalism
- Event selection for decay modes:
  - $p \rightarrow e\nu$: FCVF sub-GeV 1 ring e-like 0-decay electron events with 100 MeV $< p(e) < 1000$ MeV
  - $p \rightarrow \mu \nu$: FCVF sub-GeV 1 ring $\mu$-like 1-decay electron events with 200 MeV $< p(\mu) < 1000$ MeV
- Fit is performed for e-like and $\mu$-like momentum spectra
- Main background contribution originates from charged current CCQE (~60%) for both modes, from $\nu_\chi$ and $\nu_\tau$, with the other main contribution from pions, CC 1-3 (~15%)
- 11 dominant systematics selected for both modes, obtained from 154 official SK oscillation analysis [14] systematic errors which affect analysis bins by more than 5%
- Combined SK1-SK4 results from the fit, with residuals and 90CL amount of signal

Analysis Technique

- For processes with final state neutrinos, which are not observed at SuperK, one cannot reconstruct invariant mass and momentum of the parent particle
- Can analyze respective e-like and $\mu$-like momenta distributions
- 3-body decay implies momenta has a wide spread spectrum from 0 to ~470 MeV
- Large signal and background overlap
- Spectrum shape analyzed by employing $\chi^2$ minimization based on Poisson probability with systematic errors considered via quadratic penalties (pull terms) as in [12]

$$
\chi^2 = \sum_i \left( \frac{N_{\text{obs}} - N_{\text{theo}}}{\sigma^2} \right) + \sum_j \left( \frac{\Delta N_j}{\sigma^2} \right)
$$

- $\Delta N_j$ is the difference between observed and predicted number of events in $j$th bin
- $\sigma^2$ is the variance of the Gaussian

- $\chi^2$ is fitted to the data to obtain the best fit parameters $\lambda$ and $\beta$ (signal norm)

$$
\tau_{\text{SUSY}} = \frac{\tau_{\text{ICL}}}{B} = \frac{\lambda_1 \cdot \lambda_2 \cdot \lambda_3}{N_{\text{ICL}}}
$$

The Super-Kamiokande Detector

- Super Kamiokande is a 50 kiloton water Cherenkov detector located at Kamioka Mozumi Mine, Japan [10]
- With inner fiducial volume of 22.5 kilotons
- Built in 1996 to search for nucleon decay, study solar and atmospheric neutrinos and keep supernova watch
- In 1998, announced first evidence of neutrino oscillations [11], implying a non-zero neutrino mass

Other Novel Searches:

- $p \rightarrow eX$, $p \rightarrow \mu X$ and $n \rightarrow \nu Y$

- Important to study many modes besides most popular ones
- Use spectrum shape analysis technique already established in trilepton analysis
- Consider 2-body searches $p \rightarrow eX$ and $p \rightarrow \mu X$ where $X$ is invisible, can’t be fermion by spin conservation, can generate as neutrino in spin-independent Monte Carlo
- Previous analyses treat these as inclusive modes, assuming a specific model as SU(5) - not the case here, thus no official limits on these searches
- Some models [16] predict $n \rightarrow \nu Y$, has similar signal signature to $p \rightarrow eX$, also analyze
- The error analysis and fit is performed similarly to the trilepton mode scenario above
- The avg. total efficiency is ~90% – 70% for e-like and $\mu$-like signal momenta
- Can set lifetime limits, strongly restricting parameter space of some models [9]

References

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