PROCEEDINGS OF SCIENCE

Kaon Quenching Studies to Improve JUNO's Sensitivity to Proton Decay

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Baryon number violation is one of the proposed conditions to explain the observed matter-antimatter imbalance in our universe. Currently, the proton lower lifetime limit in the decay channel $p \to K^+ + \bar{\nu}$ has been set by the Super-Kamiokande collaboration to be $5.9 \cdot 10^{33}$ years. The Jiangmen Underground Neutrino Observatory (JUNO) aims to exceed Super-Kamiokande's lifetime limit within a few years of data taking. Cosmic muons and atmospheric neutrinos impose main backgrounds, which can be excluded primarily via the shape of the prompt scintillation signal. The presented event selection strategy results in an overall sensitivity for $p \to K^+\bar{\nu}$ of $9.6 \cdot 10^{33}$ years at 90 % C.L. based on a total exposure of 200 kton · years. JUNO's capability to contribute to the proton decay search depends on the experiment's ability to identify the kaon. The total light emission as a function of energy for a given particle species is governed by a semi-empirical model using the so-called Birks' factor kB. The UniKaon setup was developed to determine the kaon's quenching behavior at proton decay relevant energies. A prototype of the primary detector was successfully operated at a neutron beamtime at the LNL in Legnaro, Italy. First simulations have proven the vessel's shape to significantly influence the detected spectra, motivating a full light propagation simulation. Meanwhile, gain calibrations of the photomultiplier tubes for high photon yields are ongoing to improve the accuracy of determining the photon collection.

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1. Search for the Proton Decay $p \to K^+\bar{\nu}$

Grand Unified Theories (GUTs) are extensions of the Standard Particle Physics Model (SM). As the Gauge coupling scale of about 10^{16} GeV [1] lies beyond the capabilities of modern particle physics experiments, GUTs must be tested indirectly. One way is searching for the proton decay, a consequence of B-violation. The dominant proton decay mode in supersymmetric GUTs is $p \to K^+ + \bar{\nu}$ with a range for the predicted lifetime of $\tau \sim (10^{30} - 10^{35})$ years [2]. The Super-Kamiokande collaboration set the current lifetime limit of $\tau(p \to K^+\bar{\nu}) \geqq 5.9 \cdot 10^{33}$ years at a confidence level of 90 % [4] using a 50 kton ultrapure water-Cherenkov detector.

2. The JUNO Experiment and its Sensitivity to $p \to K^+\bar{\nu}$

The Jiangmen Underground Neutrino Observatory (JUNO) is a 20 kton organic liquid scintillator experiment currently under commissioning in South China (see [3]).

2.1 Proton decay signature

The kaon is emitted at kinetic energies below the Cerenkov threshold. However, its signal is visible in a liquid scintillator due to its scintillation light. After its average lifetime of 12.38 ns, the kaon decays, most likely with a branching ratio of 63.56 % to a muon neutrino and a muon, further producing a single Michel electron. The resulting overall event structure in JUNO is displayed in Figure 1. The kaon's scintillation light overlaps with its daughter's for every possible decay, leading to a double-peak structure.

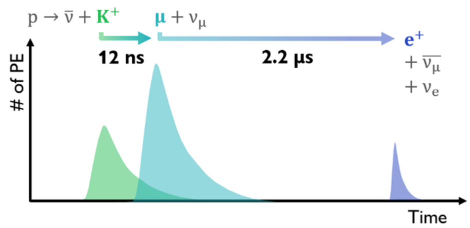

Figure 1: Illustration of the proton decay event signature in JUNO for the kaon decay to a muon.

2.2 Backgrounds

Cosmic muons and atmospheric neutrino events impose the main backgrounds. The VETO systems are expected to discriminate more than 99 % of the cosmic muons. Atmospheric neutrinos interact mainly via neutral current elastic scattering (NCES), charged current quasi-elastic scattering (CCQE), and pion and kaon production. From all possible processes, only kaon production features a double-peak prompt signal. However, its rate within the relevant energies is expected to be negligible.

2.3 Event Selection and Sensitivity Estimation

Apart from basic selection cuts on the total visible energy, the volume and a time window for the VETO systems, the number of Michel electrons and tagged neutrons, as well as the distances of secondaries to the decay position are limited. A multi-pulse fitting method is employed for the prompt signal. The prompt signal's shape is determined by comparing the χ^2 of each single-peak and double-peak model fit. From the result of the double-peak fit, additional cuts on the correlated time difference between the components and their visible energies are imposed. The described data selection strategy resulted in a detection efficiency of 36.9 ± 4.9 % at a background of $0.2 \pm 0.05(\text{syst}) \pm 0.2(\text{stat})$ for ten years. From this, an estimated sensitivity of $9.6 \cdot 10^{33}$ years at 90 % C.L., corresponding to an exposure of 200 kton · years, was determined. The partial lifetime sensitivity development with running time is depicted in Figure 2. For more information on the proposed event selection strategy and sensitivity estimations, see [5].

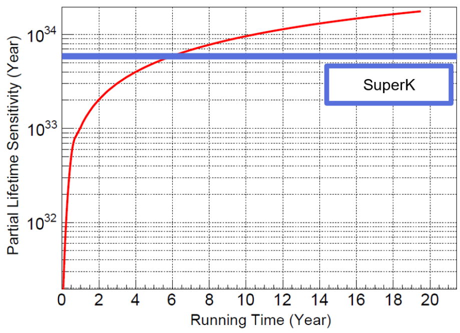

Figure 2: JUNO's estimated sensitivity to $p \to K^+\bar{\nu}$ over its runtime. The current best limit from the Super Kamiokande collaboration is expected to be surpassed after six years.

3. Kaon Quenching Studies

By understanding the kaon's scintillation behavior and thus its signal shape, the proton decay detection efficiency could be further improved. The Birks' law governs light emission in a liquid scintillator:

$$\frac{dY}{dx} = A \cdot \frac{dE/dx}{1 + kB \cdot (dE/dx)} \tag{1}$$

dY/dx and dE/dx correspond to the specific light yield and energy deposition, respectively, while A is the light emission constant. The Birks' factor kB accounts for the local density of ionized molecules specific for the traversing particle and the quenching probability [6].

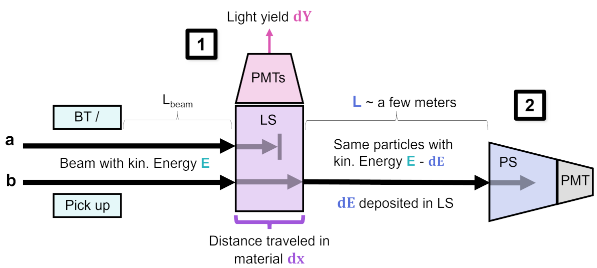

Figure 3: Illustration of the working principle of the UniKaon experiment.

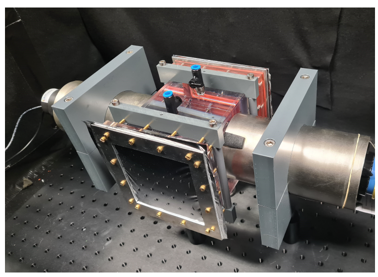

Figure 4: Mounted primary detector with the 20 cm vessel.

3.1 Experimental Setup

Due to the short kaon lifetime, measuring its Birks' factor kB is impossible. The experiment will use protons, muons, and pions at energies with the same specific energy deposition dE/dx as the kaon at around 100 MeV. To reconstruct the Birks' curves, the UniKaon setup detects the emitted light and the energy the particle deposits separately. Its working principle is depicted in Figure 3. Here, for small enough beam energies, beam (a) is entirely stopped in the primary liquid scintillator detector (Figure 4); thus, the deposited energy was the inertial one. The particles (b) can pass through for higher energetic beams or shorter vessels, and their remaining energy is determined via their time-of-flight to the second detector, which features a plastic scintillator tile and a fast-timing photomultiplier tube.

3.2 Prototype testing and calibration

A 20 cm long prototype of the liquid scintillator detector was successfully operated at a neutron beamtime at the LNL in Legnaro. Here, the time resolution of 1.34 ± 0.02 ns was dominated by the bunch width, proving sufficient timing properties for the UniKaon measurements. Additionally, the rough estimation from UniKaon of the proton quenching factor of 2-3 agreed with the high precision measurement of 3.17 ± 0.01 at a neutron energy of 2.356 MeV presented in [7]. A first simulation of the setup under the testing beamtime conditions could not replicate the detected spectra, indicating a significant influence of the vessel's shape. Meanwhile, all five vessels with lengths from 10 cm to 35 cm are calibrated with gamma sources for their light collection efficiency using mirrored foil before vacuum-coating them with an aluminum mirror. The photomultiplier tubes' gain and timing properties have been determined using a laser setup.

3.3 Conclusion

The Unikaon experiment aims to improve JUNO's sensitivity to the proton decay $p \to K^+\bar{\nu}$ of $9.6 \cdot 10^{33}$ years at 90 % C.L. by characterizing the liquid scintillator's light emission behavior for kaons at kinetic energies around 100 MeV. As the event selection strategy relies strongly on discriminating the double-peak prompt signal produced by the kaon and its daughter from single-peak atmospheric neutrino backgrounds, knowledge of the expected light yield from individual particles is crucial. Scintillation is governed by the Birks' law. Thus, the deposited energy and emitted photon count in Unikaon are determined separately by either fully stopping the beam bunches in the liquid scintillator vessel or monitoring their remaining energy via time-of-flight to a second detector. A prototype was tested under beamtime conditions at a neutron beamtime, proving sufficient timing and light collection properties. A light propagation and full waveform simulation is being implemented to study the vessel's influence on the detected spectral shape and reduce systematic uncertainties through the vessel's geometry. The PMTs' gain response to high light yields is being studied and calibration measurements with cosmic muons are planned. A first proton beamtime is expected within 2024.

4. Acknowledgements

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