GADZOOKS! Antineutrino Spectroscopy with Large Water Čerenkov Detectors

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We propose modifying large water Čerenkov detectors by the addition of 0.2% gadolinium trichloride, which is highly soluble, newly inexpensive, and transparent in solution. Since Gd has an enormous cross section for radiative neutron capture, with $\sum E_\gamma = 8$ MeV, this would make neutrons visible for the first time in such detectors, allowing antineutrino tagging by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). Taking Super-Kamiokande as a working example, dramatic consequences for reactor neutrino measurements, first observation of the diffuse supernova neutrino background, Galactic supernova detection, and other topics are discussed.

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The Super-Kamiokande (SK) water Čerenkov detector [1] has very successfully observed solar [2], atmospheric [3], and accelerator [4] neutrinos. Even more subtle signals could be studied if antineutrinos were tagged by the detection of neutrons following $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$), as the coincidence detection greatly reduces backgrounds from radioactivities and other neutrino reactions. We propose that this could be accomplished by the addition of 0.2% gadolinium trichloride ($GdCl_3$) to the water, and refer to the resulting detector as GADZOOKS! (*Gadolinium Antineutrino Detector Zealously Outperforming Old Kamiokande, Super!*). While this ability exists in $\lesssim 1$ kton detectors, it has never been achieved on the scale of the 22.5 kton fiducial mass of SK, nor in a light water detector. The proposed use of $GdCl_3$ dissolved in water is also novel. We discuss SK as a concrete example to show feasibility, but the proposed technique has much more general applicability.

Neutron Capture on Gadolinium.— Neutrons in water quickly lose energy by collisions with free protons (and oxygen nuclei); once thermal energies are reached, the neutron continues to undergo collisions, changing its direction, but on average not its energy, until it is captured [5]. The cross section for thermal neutron capture on natural Gd is 49000 barns, compared to 0.3 barns on free protons [6]. With the proposed 0.2% admixture by mass of $GdCl_3$ in water, 90% of neutron captures are on Gd (8 MeV gamma cascade), 0.2% on Cl (8.6 MeV gamma cascade), and the rest on H (2.2 MeV gamma, not detectable in SK). After thermalization, capture occurs in about 20 μs (about 10 times faster than in pure water) and about 4 cm; both are slightly increased by the pre-thermalization phase. Compared to typical time and distance separations between events in SK, as well as the position resolution, these are exceedingly small.

Since SK was first proposed, the price of the water soluble salt $GdCl_3$ has fallen three orders of magnitude, most of that in the past few years. The current price of 99.99% pure $GdCl_3 \cdot X H_2O$ from the Stanford Materials Corporation is about \$3/kg. The properties of $GdCl_3$ are discussed in more detail below. Neutron capture on Gd leads to 8 MeV shared among $3-4$ gammas. In scintillators, where Gd is used routinely, the summed gamma energy is relevant. However, in water what matters are the electrons Compton-scattered above the Čerenkov threshold by relatively hard gammas. The detectable light following neutron capture on Gd (in thin foils) in possible discrete counters was carefully simulated [7] for the SNO heavy water Čerenkov detector. The equivalent single electron energy was found to peak at about 5 MeV, and range over $3-8$ MeV. This spread reflects the intrinsic variation in the gamma cascades and the detector energy resolution (the simulation had 5 photoelectrons per MeV of electron energy, compared to 6 in SK-I).

At energies as low as 3 MeV, background singles rates are much too high to detect neutron captures in isolation, as required in SNO. However, using the detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ and requiring a very tight time and position coincidence between the positron and the following neutron will allow detection of nearly all captures on Gd. Due to continuing improvements in online data acquisition and filtering, it is expected that SK-III, which will begin operations in mid-2006, will trigger at 100% efficiency at 3 MeV and above, with good trigger efficiency down to 2.5 MeV. The rate of accidental coincidences is vanishing, since the number of candidate solar neutrino events is ~ 1/yr/ton in SK. Gamma cascades also produce more isotropic light than other backgrounds, which aids in their identification.

Neutron Rates in SK.— The ambient neutron rate in the SK fiducial volume is unknown, as neutrons and their captures on free protons are invisible. Though a high background neutron rate could be tolerated for the coincidence signal $\bar{\nu}_e + p \rightarrow e^+ + n$, we do not want to compromise the $5-20$ MeV solar neutrino singles signal by making neutron captures visible. There are ~ 10 signal events per day along the solar direction, and ~ 100 background events per day over all directions. After examining a wide variety of potential sources of ambient neutrons, we find that they are not a problem.

Cosmic ray muon spallation in SK produces a very steeply falling spectrum of $\sim 10^5$ neutrons/day; their production is of interest [8]. Spallation also produces beta-unstable daughters that form a significant background for solar neutrinos; after cuts following muons, $\lesssim 100$ spallation betas/day survive. Since these cuts veto events within seconds and meters of muon tracks, they will be much more effective on neutrons, which capture in much less time and distance. Neutrons from spallation events in the surrounding rock are stopped by 4.5 m of water shielding surrounding the fiducial volume. Our conclusions are supported by data from KamLAND, which is adjacent to SK and has similar shielding [9]. Dissolved Gd would also be present in the optically isolated outer detector, and the neutron capture rate there could be as high as 10^3 Hz, due to neutrons from the surrounding rock [1]. However, captures on Gd would not produce enough light to trigger the sparse outer detector.

The rate of $\bar{\nu}_e + p \rightarrow e^+ + n$ interactions in SK from nuclear reactors is $\simeq 30$/day. For the majority of events the positron would be detectable in coincidence with the neutron (even without that, the excess singles rate due to neutron captures could be detected). For the lowest energy reactor antineutrinos, as well as those originating from U/Th decays in Earth, the positron energy is too low to trigger SK, and the neutron would appear in isolation. The rate due to U/Th decays is expected to be ~ 4/day. Atmospheric neutrino neutral-current events may be otherwise invisible if only a neutron is scattered, a relatively common event, at a rate of ~ 2/day.

At the present U/Th/Rn concentrations in SK, $\lesssim 1$ neutron/day in total is produced by the following processes: spontaneous fission of ^{238}U; (α, n) reactions on ^{2}H, ^{17}O, and ^{18}O; and ^{2}H(γ, n); estimated by scaling from SNO results [10]. The $GdCl_3$ additive must meet radiopurity standards about 10^3 times less stringent than for the SK water. Initial test samples, for which no special care was taken, were measured by mass spectroscopy to have $[^{238}\mathrm{U}] \simeq 10^{-8}$ g/g and $[^{232}\mathrm{Th}] \simeq 10^{-10}$ g/g [11]. Assuming secular equilibrium in the decay chains, the beta and neutron rates in SK would remain similar to present values if the samples were purified by a factor of 100. The Palo Verde experiment obtained Gd 10 times more radiopure than our initial samples, and the SK water system reduces U/Th/Rn by orders of magnitude from the original mine water. We are confident that the desired radiopurity is easily obtainable (as was Ref. [7]).

Natural Gd contains 0.2% ^{152}Gd, which alpha decays ($T_{1/2} = 10^{14}$ yr, $T_\alpha = 2.1$ MeV) [6]. With 100 tons of $GdCl_3$ in SK, the decay rate is $\sim 10^{10}$/day. These alphas are invisible in SK, but their introduction may initiate ^{17}O(α, n) and ^{18}O(α, n) reactions. Using the alpha stopping power and the measured cross sections [12], the neutron production rate is ~ 1/day. Lanthanide contaminants ($\lesssim 10^{-4}$) and their decays can also be ignored.

Reactor Neutrinos.— The total $\bar{\nu}_e + p \rightarrow e^+ + n$ rate in SK from reactors can be scaled from the KamLAND rate [9], and is $\simeq 30$/day after oscillations. The threshold for solar neutrinos in SK-I was $E_e = 5$ MeV, and SK-III should be even better due to a lowered trigger threshold and much-improved offline reconstruction algorithms currently being evaluated in SK-II. This was the *analysis* threshold for single events. The trigger is efficient to much lower energies (as low as 3.5 MeV in SK-I), where radioactivity backgrounds overwhelm the solar singles rate. However, for the coincidence signal, it should be possible to identify real events as low as $E_e = 2.5$ MeV, covering most of the reactor spectrum. The present KamLAND analysis threshold is $E_{vis} = T_e + 2m_e = 2.6$ MeV, corresponding to $E_e = 2.1$ MeV in SK. Measurement of the positron energy determines the neutrino energy, since $E_\nu \simeq E_e + 1.3$ MeV, and additionally there is a weak directional correlation [5].

GADZOOKS! would have the advantage of much larger statistics, with about 50 times more fiducial mass. The very high rate would allow the flux to be monitored on yearly basis with about 1% statistical error, likely allowing new tests of neutrino oscillation parameters as reactors at different distances go through on/off cycles. The expected reactor spectrum is shown in Fig. 1. The energy resolution in SK is about 6 times worse than in KamLAND, so that spectral distortions (not shown) will be smeared, though high statistics may still reveal them. Resolution is why the positron spectrum extends to $E_e = 12$ MeV, even though the neutrino spectrum [13] plummets beyond $E_\nu = 8$ MeV.

In KamLAND, fast neutrons from the walls can scatter protons (producing scintillation light) and then capture, mimicking the coincidence signal; in SK, the struck protons are invisible. Muon spallation produces three isotopes (^{8}He, ^{9}Li, and ^{11}Li) that beta decay to excited daughter states that decay by neutron emission [6]. In KamLAND, spallation cuts control these to be $\lesssim 2\%$ of the reactor signal. Spontaneous fission of ^{238}U and atmospheric neutrino neutral-current interactions can both produce multiple neutron events that can mimic the reactor signal, but the rates are small.

Diffuse Supernova Neutrino Background.— From a supernova in the nearest galaxy, Andromeda, SK would detect ~ 1 event. While more distant galaxies have lower fluxes, there are many more of them, and the flux from all previous core-collapse supernovae in the universe may be detectable. We refer to this as the *Diffuse Supernova Neutrino Background* (DSNB), and not the more common "relic supernova neutrinos," since the latter causes confusion with "relic" big bang neutrinos. All neutrino flavors are produced, but $\bar{\nu}_e$ is the easiest to detect, via $\bar{\nu}_e + p \rightarrow e^+ + n$ on free protons. The strongest limits are from SK, based on the electron spectrum above 18 MeV (at 18 MeV, the measured rate is $\sim 1/22.5$ kton/yr/MeV) [14]. The DSNB spectrum is a convolution of a single supernova spectrum with the supernova rate as a function of z, with neutrino energies redshifted as $E_\nu/(1+z)$. The Kaplinghat, Steigman, and Walker (KSW) model pushed uncertainties in the direction of producing the largest reasonable DSNB flux [15]. In the relevant energy range, $E = 10 - 30$ MeV, other models have nearly the same shape but differ mostly in normalization; also, several uncertainties are minimized. The supernova rate is reasonably known in the relevant range $z \lesssim 1$ (where it rises by ~ 10 over the $z = 0$ rate) [15, 16]. Uncertainties on cosmological and neutrino oscillation parameters no longer play a significant role [16], the latter especially if realistic neutrino temperatures [17] are used. The DSNB detection cross section [5] may be treated at lowest order at present.

In Fig. 1, we show a range of DSNB spectra. The upper edge of the band is set by the SK limit [14] (0.6 of KSW), and the lower edge by modern models [16] (0.2 of KSW). The background-limited SK search [14] will gain the required factor of 3 in sensitivity in about 40 years. In GADZOOKS!, this sensitivity would be available immediately. Requiring neutron detection would dramatically lower the backgrounds below 18 MeV, where the spallation beta singles rate rises rapidly. As the threshold is lowered, the atmospheric neutrino backgrounds fall and the DSNB signal rises. We calculate that the atmospheric [18] backgrounds can be reduced by ~ 5 from the measured rates [14] by rejecting events with a preceding nuclear gamma [19] or without a following neutron. Further rejection (not shown) is likely possible by requiring a small position separation between prompt and delayed events, since DSNB events produce much less energetic neutrons. The number of DSNB events expected in GADZOOKS! is about $2 - 6$ per year above 10 MeV. Uncertainties smaller than the corresponding Poisson uncertainty can be ignored.

Detection of the DSNB would be an extremely important scientific milestone. It could be the first detection of neutrinos from significant redshifts $z \lesssim 1$, and the second detection of supernova neutrinos. With the exception of SN 1987A in the Large Magellanic Cloud, a close companion of our Galaxy, neutrinos have never been detected from farther than the Sun. The DSNB flux is proportional to the rate of all core-collapse supernovae, including optically dark "failed" supernovae that collapse to black holes. The DSNB spectrum shape would also provide a crucial calibration for numerical supernova models, since in relatively few years, the sample of neutrinos from SN 1987A could be surpassed

Galactic Supernova.— Supernovae in our Galaxy are expected about 3 times per century, and SK would observe $\sim 10^4$ events at a typical distance of 10 kpc. The ability to cleanly identify the dominant $\bar{\nu}_e + p \to e^+ + n$ events would be extremely important for studying the remaining reactions, notably $\nu_e + ^{16}\mathrm{O} \to e^- + ^{16}\mathrm{F}$, which is exquisitely sensitive to the ν_e temperature and hence neutrino mixing [20]. Hundreds of ν_e events could be observed, far more than in any other detector. The neutral-current events on ^{16}O that lead to gamma and/or neutron emission would be much better identified, of key importance for measuring the ν_μ/ν_τ temperature [21]. Even in the forward angular cone, inverse beta events dominate neutrino-electron scattering events [22]. Isolating those events would be very useful: it would help detect the neutronization burst ν_e events; it would improve the pointing to the supernova by a factor of about 2, down to about 2° [22]; and it would allow better spectral studies. Using timing information alone, SK could immediately recognize a supernova as genuine by the unique time structure of the events: almost all events in pairs separated by tens of microseconds, much shorter than the separation between subsequent neutrino interactions. Neutron detection would improve the ability to study bursts out to very late times, or to detect faint bursts.

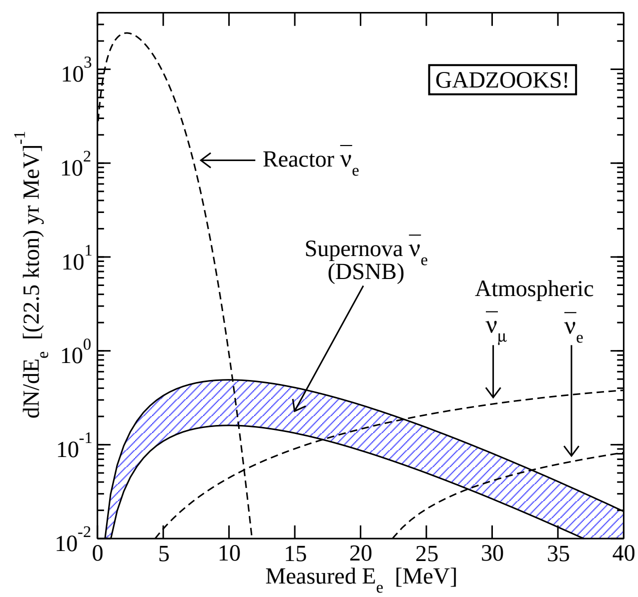

FIG. 1: Spectra of low-energy $\bar{\nu}_e + p \to e^+ + n$ coincidence events and the sub-Čerenkov muon background. We assume full efficiencies, and include energy resolution and neutrino oscillations. Singles rates (not shown) are efficiently suppressed.

Other Physics.— The solar $\bar{\nu}_e$ flux is $\lesssim 1\%$ of the predicted ν_e flux [23]. Requiring a neutron coincidence would greatly reduce backgrounds, and the sensitivity would be better than about 0.01%; the weak directional information [5] may allow even better sensitivity. For atmospheric and accelerator neutrinos, the ability to detect neutron captures delayed from the neutrino interaction would shed new light on the hadronic final state. This would be useful for separating (especially sub-GeV) neutrinos and antineutrinos (which preferentially eject protons and neutrons, respectively) and for probing the type of neutrino interaction. For accelerator neutrinos, neutrino-neutron elastic scattering will be a significant new neutral-current channel. For proton decay, neutron detection may reduce atmospheric neutrino backgrounds, as well as aid the study of bound-nucleon decay modes (including invisible modes) in which the final nucleus decays with an emitted neutron.

R&D on GADZOOKS!— Many of the properties of $GdCl_3$ are already well known. It is naturally highly water soluble, in concentrations up to 50%. In contrast, an elaborate chemistry is needed to suspend even modest amounts of Gd in liquid scintillator. $GdCl_3$ is stable, nonreactive, and easy to handle in bulk quantities. Years of human and animal studies have demonstrated its nontoxicity [24], and it is commonly employed as a safe and effective contrasting agent in human MRI subjects. Still, because of the novel use we are proposing for $GdCl_3$, some new, specialized information is desired.

In our calculations, we treated neutron capture on Gd, but otherwise ignored the effects of $GdCl_3$ on the detector (note that Haxton discussed adding $5-10\%$ admixtures of various other salts to SK as solar neutrino targets, but not for neutron capture [25]). Three key R&D issues are currently being addressed [26]. First, while preliminary measurements indicate that the light absorption length over the Čerenkov frequency range in Gd-loaded SK water remains $\gtrsim 100$ m [11], its complete light attenuation characteristics (including scattering) over these long distances will be evaluated. Second, the physical effects of $GdCl_3$ on detector components will be investigated through extended exposure of samples of these materials, as well as through the use of established accelerated aging techniques. Finally, an operational replica of the SK water filtration system will be constructed in order to determine the most effective method of filtering the water of other impurities without incurring unacceptable losses or concentration variations of the 0.2% $GdCl_3$ solute in the process.

Conclusions.— We propose GADZOOKS!, a large water Čerenkov detector that would allow neutron detection by radiative capture on a dissolved gadolinium salt. Extensive research and preliminary R&D, briefly reported here, strongly support the feasibility of this technique, and a program of focused R&D has just been funded [26]. The new ability to detect neutrons in a large light water detector would allow the clear identification of $\bar{\nu}_e$ by the coincidence detection reaction $\bar{\nu}_e + p \rightarrow e^+ + n$ (similarly for $\bar{\nu}_\mu$). An entirely new program of antineutrino spectroscopy would be opened, with important implications for reactor, solar, supernova, atmospheric, and accelerator neutrinos. The prospects for the first detection of the diffuse supernova neutrino background are particularly exciting. This could be the first detection of neutrinos from cosmological distances (and certainly the largest L/E), and the second detection of supernova neutrinos. In just a few years, the yield from SN 1987A could be surpassed. Unlike previous neutron detection techniques, ours is scalable at reasonable expense. Megaton-scale water detectors with $GdCl_3$ could observe hundreds of DSNB events per year, allowing stringent tests of the black hole formation rate and supernova neutrino spectra. Other physics topics would enjoy similar benefits.

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