Radiochemical Neutrino Detection via $^{127}I(\nu_e, e^-)^{127}Xe$

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Solar or supernova neutrinos incident on an iodine-bearing liquid will produce the noble gas ^{127}Xe ($\tau_{1/2}=36.4$ d), which can be recovered and counted as in the present ^{37}Cl experiment. The rate of neutrino reactions per unit volume of detector could be more than an order of magnitude greater than in perchloroethylene. I discuss the new physics that might be learned from such an experiment.

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I will argue below that a radiochemical detector employing an iodine-bearing liquid could serve as a sensitive observatory for astrophysical neutrinos. The operative reaction, $^{127}I(\nu_e,e)^{127}Xe$ ($\tau_{1/2}=36.4$ d), is strikingly similar[1] to the reaction $^{37}Cl(\nu_e,e^-)^{37}Ar$ ($\tau_{1/2}=35.0$ d) employed by Davis and co-workers in the current Homestake experiment.[2] It appears that the recovery and counting of the noble-gas product ^{127}Xe can be performed with existing techniques, and that the capture rate per unit detector volume could exceed that in perchloroethylene by more than an order of magnitude. I argue that calibration experiments should be mounted to determine whether ^{127}I is primarily a ^7Be or an ^8B solar-neutrino detector. I also discuss the sensitivity of such a detector to neutrinos from galactic supernovae.

Some of the relevant nuclear structure is illustrated in Fig. 1. Neutrinos with $\epsilon_\nu \geq 664$ keV can interact with ^{127}I (abundance=100%) to produce ^{127}Xe, which then captures an electron as it decays back to the parent nucleus with a half-life of 36.4 d. As the $\frac{5}{2}^+ \to \frac{1}{2}^-$ transition to the ^{127}Xe ground state is forbidden, the cross section for capturing ^7Be neutrinos ($\epsilon_\nu=862$ keV) should depend only on the strength of the Gamow-Teller[3] $\frac{5}{2}^+ \to \frac{3}{2}^+$ transition to the 125-keV state. The high-energy ($\simeq$14-MeV end point) ^8B solar neutrinos can produce ^{127}Xe by exciting many transitions to states below the threshold for neutron breakup, 7.23 MeV above the ground state.

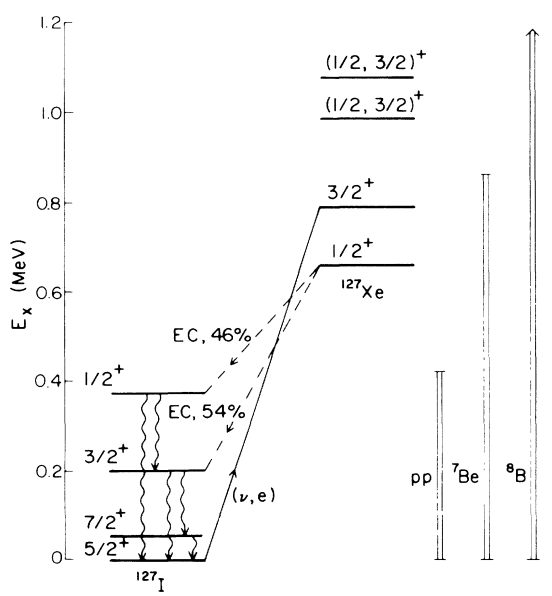

FIG. 1. Level scheme showing weak transitions between ^{127}I and ^{127}Xe.

The strengths of the relevant Gamow-Teller (GT) transitions are not presently known. In recent years it has been demonstrated empirically that the forward-angle (p,n) reaction at medium energies can be used to calibrate GT strengths. This technique provided an estimate of the excited-state contributions to the ^{71}Ga neutrino-capture cross section,[4] and yielded a ^{37}Cl capture cross section in good agreement with other determinations.[5] Though the accuracy of this technique is difficult to quantify, $\pm 20\%$ may be a reasonable estimate for the anticipated ^{127}I ^8B cross-section uncertainty.[6] For the present discussion I have made a rough estimate of the ^{127}Xe GT distribution between threshold and neutron breakup by scaling the measured ^{71}Ga[4] and ^{98}Mo[7] GT distributions by the appropriate ratios of N-Z factors, in accordance with the naive sum rule. On folding with the proper phase-space factors, one obtains cross sections averaged over the ^8B neutrino spectrum of 7.2×10^{-42} cm^2 and 8.9×10^{-42} cm^2, respectively. I adopt the smaller value, with the caution that the uncertainty in this estimate is large. The large cross section is due in part to Coulomb effects, which enhance the phase space by a factor of 2 in going from $Z=31$ (Ga) to $Z=53$. For comparison, the ^{37}Cl ^8B cross section is 1.12×10^{-42} cm^2.[5]

The strength of the ^7Be-neutrino $\frac{5}{2}^+ \to \frac{3}{2}^+$ (125 keV) transition could be determined from (p,n) measurements, with the assumption that sufficient resolution is achieved, or directly calibrated in a neutrino-source experiment. Neighboring states at 321 and 412 keV have been identified only as $J^\pi=(\frac{1}{2},\frac{3}{2})^+$. If the 321-keV state has $J=\frac{3}{2}$, a resolution of approximately 200 keV is required to separate this transition from that to the 125-keV level. This is comparable to the best

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achieved to date in (p,n) GT measurements. Clearly an experiment to determine the spins of the 321- and 412-keV states is important. Note that the threshold for exciting the 125-keV state rules out direct calibration by a ^{51}Cr source ($\epsilon_\nu = 746$ keV). A ^{65}Zn source ($\epsilon_\nu = 1343$ keV) is sufficiently energetic, but could excite other GT transitions to states below 680 keV in ^{127}Xe, if indeed such transitions exist.

The ^{7}Be cross section can be expressed in terms of the unknown ft value for the $\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ transition:

$$\sigma(^7\mathrm{Be}) = (1.98\times 10^{-45}\,\mathrm{cm}^2)\left[10^5\,\mathrm{sec}/ft\right]. \qquad (1)$$

For $\log_{10}[ft\ (\mathrm{sec})] = 5.11$, the ratio $\sigma(^8\mathrm{B})/\sigma(^7\mathrm{Be})$ has the same value as in the ^{37}Cl experiment, 4.7×10^3, and the two experiments would test very similar physics. If the transition is much stronger ($\log_{10} ft \lesssim 4.8$) or much weaker ($\log_{10} ft \gtrsim 5.4$), the ^{127}I experiment would have significantly greater sensitivity to ^{7}Be or ^{8}B neutrinos, respectively, and important new physics could be learned. Thus a careful measurement of this ft value is needed.

An experiment could be performed by use of a tank, similar to that now in place in the Homestake mine, with a suitable iodine-bearing liquid. Although a number of suitable organic liquids are available in commercial quantities (methylene iodide, ethyl iodide, phenyl iodide), a similar alternative may be a water solution of iodine and one of the common salts (NaI, KI, NH_4I). As elemental iodine easily dissolves in salt solutions due to the formation of polyiodide ions, rather extraordinary ($\simeq 87\%$) iodine concentrations can be achieved: A solution in equilibrium with solid iodine and $(KI)\cdot H_2O$ at 25 °C contains 67.8% iodine, 25.6% KI, and 6.6% water.[8]

Iodine is not as attractive as chlorine in either commercial availability or cost, and normally this would pose a serious obstacle to an experiment. However, the U.S. government has about 3.1×10^6 kg of iodine in its stockpile,[8] about $\frac{1}{3}$ of which is viewed as excess and is scheduled to be sold. This excess is approximately the amount needed if one were to fill a tank like that at Homestake with a concentrated iodine solution. This seems like a happy coincidence that should be exploited.

Xenon extraction from a liquid target presumably could be accomplished by He flushing, the method developed at Homestake. In a 20-h extraction period about 4×10^5 l of He are passed through the Homestake tank (which contains 3.8×10^5 l of perchloroethylene) and extraction system, removing about 95% of the argon. The extraction rate for krypton, which is more soluble than argon in organic liquids, was determined to be 40% that for argon.[2] Thus, to remove 95% of the contained krypton, about 10^6 l of He must be forced through the tank. Presumably the Homestake extraction system would also function well for Xe, though this should be verified by introduction of a small amount of Xe tracer into the Homestake tank and measurement of its extraction during subsequent ^{37}Cl solar-neutrino runs.

The ^{127}Xe atoms extracted in this manner could be counted as they decay back to ^{127}I with a half-life of 36.4 d. In ^{37}Ar the decay proceeds to the ground state of ^{37}Cl, so that low-energy Auger electrons provide the only signal for the electron capture. In ^{127}Xe the decay proceeds exclusively to excited states in ^{127}I, populating the $\frac{1}{2}^+$ (375 keV) and $\frac{3}{2}^+$ (203 keV) levels with branching ratios of 46% and 54%. These states decay primarily by γ emission, as illustrated in Fig. 1. Thus the counting of ^{127}Xe can be done by our measuring the Auger electrons and γ's in coincidence, thereby obtaining an extremely low background rate. One could count the ^{127}Xe in a small proportional detector[2] surrounded by a 4π sodium iodide or germanium detector. Both the singles and coincidence rates could be recorded if the counting were performed underground.[9]

We can now sketch the possible results of a ^{127}I experiment. For a detector tank similar to that at Homestake, one obtains the ^{127}Xe production rate (assuming a target of 380 000 l of methylene iodide, for definiteness)

$$R(^{127}\mathrm{Xe}) = (20.5/\mathrm{d})\tilde\phi(^8\mathrm{B}) + (4.5/\mathrm{d})[(10^5\,\mathrm{sec})/ft][\tilde\phi(^7\mathrm{Be}) + 0.12\tilde\phi(pep) + 0.08\tilde\phi(^{13}\mathrm{N}) + 0.21\tilde\phi(^{15}\mathrm{O})], \qquad (2a)$$

which can be compared to the ^{37}Ar production rate in the Homestake tank,

$$R(^{37}\mathrm{Ar}) = (1.22/\mathrm{d})\tilde\phi(^8\mathrm{B}) + (0.21/\mathrm{d})[\tilde\phi(^7\mathrm{Be}) + 0.20\tilde\phi(pep) + 0.09\tilde\phi(^{13}\mathrm{N}) + 0.31\tilde\phi(^{15}\mathrm{O})], \qquad (2b)$$

where $\tilde\phi(^7\mathrm{B})$ denotes the ^{8}B-neutrino flux in units of the standard-model flux.[10] In Eq. (2a) I have included only the $\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ transition in estimating the CNO and pep neutrino contributions. The rough estimates made here suggest that a ^{127}I detector could be a factor of 17 more sensitive to ^{8}B neutrinos and a factor of 21 [$(10^5$ sec$)/ft$] more sensitive to ^{7}Be neutrinos than the ^{37}Cl detector. In particular, for a low-Z nonstandard solar model[10] that reproduces the observed counting rate in the Homestake detector (0.38 ± 0.05 ^{37}Ar atoms/d above known backgrounds),

$$R(^{127}\mathrm{Xe}) = \{3.69 + 2.65[(10^5\,\mathrm{sec})/ft]\}/\mathrm{d}.$$

The large capture rate has a number of important implications. One is the possibility of a calibration with an intense neutrino source. Apart from geometrical details, the success of a calibration depends on having a high density of target atoms and a large cross section for absorbing the neutrinos produced by the source. The product of these quantities thus forms an important "figure of merit." The ratio of these products for the ^{127}I and ^{71}Ga experiments (with the assumption of an 8.4 molar $GaCl_3$ target, a ^{65}Zn source for the ^{127}I calibration, and a ^{51}Cr source of equal intensity for the ^{71}Ga calibration) is 4.23 $[(10^5\ \mathrm{sec})/ft]$. In addition, the geometry will favor the larger ^{127}I detector. Thus a calibration may well determine whether the $\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ transition will lead to significant ^{7}Be-neutrino capture. A second advantage of a larger counting rate is the possibility of the exploitation of the eccentricity of the Earth's orbit ($2\epsilon = 0.0335$) to demonstrate that the neutrino signal is solar in origin. Garvin, Kopylov, and Streltsov have argued that a 3000-ton C_2Cl_4 detector producing 1.9 ^{37}Ar atoms/d might permit this over the course of a 10-yr experiment.[11] The ^{127}Xe production in the smaller detector under discussion here would very likely exceed this rate.

However, I believe the most important aspect of a large capture rate is in reducing the counting fluctuations in individual runs, thereby making the detector more sensitive to anomalous events. Rowley, Cleveland, and Davis have summarized a maximum likelihood analysis of the production, separation, and counting of ^{37}Ar in a simple formula for the 1σ error E in the production rate per run[2]:

$$E^2 = (0.027/x)(+3.7B/x), \tag{3}$$

where $x = \epsilon SP$, B is the background counting rate per day, ϵ is the fractional counting efficiency, P is the number of ^{37}Ar atoms produced per day, and S is the saturation factor, defined by $S = 1 - \exp(-\lambda t_e)$. Here λ is the decay constant for ^{37}Ar and t_e is the exposure time. For the ^{37}Cl experiment, $P = 0.47$, $\epsilon = 0.40$, and B is about 0.01. Given an exposure time of 60 d one finds a fractional error of $E = 0.51$. As the background term is small ($3.7B/x = 0.28$), this large error is attributable to the low counting rate.

Assuming a comparable counting efficiency and background rate for the ^{127}I, one obtains

$$E(^{127}\mathrm{I}) = 0.16/\{1 + 0.72[(10^5\ \mathrm{sec})/ft]\}^{1/2}$$

for low-Z "consistent" model fluxes.[10] Consider the implications of this smaller fractional uncertainty for the detection of galactic supernovae. The capture cross section for a normalized Fermi-Dirac neutrino distribution with a temperature $T = 5$ MeV is 0.98×10^{-40} cm^2 [estimated from the Ga(p,n) profile, as described earlier]. The number of ^{127}Xe atoms produced in a 380000-l tank of methylene iodide is

$$147 \left(\frac{10\ \mathrm{kpc}}{d}\right)^2 \left(\frac{E}{0.8 \times 10^{53}\ \mathrm{ergs}}\right),$$

where d is the distance to the supernova and E is the total energy emitted in ν_e's. Thus, for a 60-d run, one obtains an "nE" effect above the solar-neutrino "background," where

$$n = \frac{4.15}{\{1 + 0.72[(10^5\ \mathrm{sec})/ft]\}^{1/2}} \times \left(\frac{10\ \mathrm{kpc}}{d}\right)^2 \left(\frac{E}{0.8 \times 10^{53}\ \mathrm{ergs}}\right).$$

(Of course, if the event occurs near the beginning of the run, one would flush the tank immediately and get a more significant signal.) One sees that the detector has a range comparable to the galactic radius.

Finally, while a quantitative discussion of backgrounds must be given elsewhere, qualitative arguments suggest that a ^{127}I experiment is also attractive from this perspective. The principle background sources are (1) cosmic-ray muons, (2) energetic α particles, (3) slow neutrons, and (4) fast neutrons. Cosmic-ray muons yield spallation protons that produce ^{127}Xe principally by the reaction ^{127}I(p,n)^{127}Xe. However, relative to perchloroethylene, the stronger nuclear Coulomb field suppresses the (p,n) reaction while enhancing the solar-neutrino capture rate. Energetic α's from uranium and thorium produce ^{127}Xe by ^{124}Te(α,n)^{127}Xe and ^{123}Te(α,γ)^{127}Xe, analogs of ^{34}S(α,n)^{37}Ar and ^{38}S(α,γ)^{37}Ar. Both the Q values and the Coulomb barriers are much less favorable for the reactions on Te. Energetic α's can also produce ^{127}Xe by the two-step process (α,p) followed by ^{127}I(p,n)^{127}Xe, in analogy with ^{35}Cl(α,p)^{38}Ar followed by ^{37}Cl(p,n)^{37}Ar. However, for ^{127}Xe, the (α,p) reactions that could occur on carbon or iodine in an organic liquid are endothermic [unlike ^{35}Cl(α,p)], and the Coulomb barrier again suppresses the (p,n) rate. The slow-neutron capture rate ^{126}Xe(n,γ)^{127}Xe will be a tiny fraction of the ^{36}Ar(n,γ)^{37}Ar rate: The thermal-neutron capture cross section for ^{126}Xe is smaller, and the atmospheric abundance of ^{126}Xe is negligible compared to that of ^{36}Ar. In perchloroethylene fast neutrons produce ^{37}Ar by the reaction ^{35}Cl(n,p)^{35}S followed by ^{37}Cl(p,n)^{37}Ar. Coulomb barriers [and Q values, in the case of the (n,p) reaction on carbon] suppress the analogous reactions in methylene iodide. Finally, the reaction ^{130}Ba(n,α)^{127}Xe can be induced by fast neutrons. While the Q value favors this reaction by almost 5 MeV over the analog reaction ^{40}Ca(n,α)^{37}Ar, the difference in the α-particle Coulomb barriers ($\simeq 6$ MeV) compensates for this. Furthermore, the concentration of ^{40}Ca (97% abundant) in a detector is likely to far exceed that of ^{130}Ba (0.1% abundant). In conclusion, pending more careful calculations (or measurements), these background estimates are encouraging.

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[1]Iodine appeared on Davis's original list of low-energy β emitters, with the notation "looks familiar." [R. Davis, Jr., in Proceedings of the Irvine Solar Neutrino Conference, San Clemente, California, edited by F. Reines and V. Trimble, 1972 (unpublished)]. As the g.s.$\rightarrow$g.s. transition is weak, the analog state is unbound, and no tool was then available for the measurement of GT strength to excited states, ^{37}Cl would have looked more attractive. I could find no subsequent discussion of iodine as a solar-neutrino detector.

[2]J. K. Rowley, B. T. Cleveland, and R. Davis, Jr., in *Solar Neutrinos and Neutrino Astronomy—1984,* edited by M. L. Cherry, K. Lande, and W. A. Fowler, AIP Conference Proceedings No. 126 (American Institute of Physics, New York, 1984), p. 1.

[3]The final state in ^{127}Xe is identified only as $(\frac{3}{2}^+)$ in the standard compilation, A. Hashizume *et al.*, Nucl. Data Sheets **35**, 181 (1982). However, the cited references identify this state as $\frac{3}{2}^+$: A. Spalek *et al.*, Z. Phys. **204**, 129 (1967); I. Rezanka *et al.*, Nucl. Phys. **A141**, 130 (1970); W. Gelletly *et al.*, J. Phys. G **2**, 811 (1976).

[4]D. Krofcheck *et al.*, Phys. Rev. Lett. **55**, 1051 (1985). These data were renormalized downward by 30% to agree with newer, low-background (p,n) measurements (J. Bahcall, private communication).

[5]J. Rapaport *et al.*, Phys. Rev. Lett. **47**, 1518 (1981).

[6]T. N. Taddeucci *et al.*, Nucl. Phys. **A469**, 125 (1987), argue that relative cross sections can be determined to 5% in this way. However, the data that demonstrate this are largely confined to light nuclei. By normalization to the (continuum) Fermi transition, the GT cross sections can be extracted under the assumption that isospin mixing and the GT "background" in the Fermi peak are small. However, a neutrino-source calibration of the $\frac{5}{2}^+ \rightarrow \frac{3}{2}^+$ transition would provide an absolute normalization, since differences in Fermi and GT distortion factors would not be a concern.

[7]J. Rapaport *et al.*, Phys. Rev. Lett. **54**, 2325 (1985).

[8]C. J. Mazac, in *Encyclopedia of Chemical Technology,* edited by H. F. Mark *et al.* (Wiley, New York, 1981), Vol. 13, pp. 649–677; T. Michaels, private communication, who suggested that the solution be stabilized by hydrazine, a reducing agent.

[9]I acknowledge very helpful comments from Frank Avignone.

[10]J. N. Bahcall and R. Ulrich, Rev. Mod. Phys. (to be published). The values used, in units of $10^{10}/\mathrm{cm}^2$ sec, are $\phi(pp)=6.0$ (6.4), $\phi(pep)=0.014$ (0.015), $\phi(^7\mathrm{Be})=0.47$ (0.18), $\phi(^8\mathrm{B})=5.8\times10^{-4}$ (1.05×10^{-4}), $\phi(^{13}\mathrm{N})=0.061$ (0.016), and $\phi(^{15}\mathrm{O})=0.052$ (0.013) for the standard ("consistent" low-Z) model.

[11]V. N. Garvin, A. V. Kopylov, and A. V. Streltsov, in Ref. 2.