Proposed Solar-Neutrino Experiment Using ^{71}Ga

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(Received 20 March 1978)

A solar-neutrino experiment that uses ^{71}Ga as a detector can distinguish between broad classes of explanations for the discrepancy between prediction and observation in the ^{37}Cl experiment. A radiochemical experiment with the required amount of ^{71}Ga is feasible.

The results of the ^{37}Cl solar-neutrino experiment are in disagreement with the predictions made using a standard model of the solar interior.[1] Many authors have argued that this discrepancy shows that the standard theory of stellar evolution is wrong in some basic aspect and have proposed conceivable ways of modifying the conventional assumptions that are used in stellar model calculations. Other authors have suggested that neutrinos produced in the interior of the sun do not reach the earth, at least not in the form or quantity in which they are emitted. We show in this Letter that these two broad classes of explanation can be distinguished by a feasible experiment involving the reaction

$$\nu_{e,\text{solar}} + {}^{71}\text{Ga} \to e^- + {}^{71}\text{Ge} \quad (1)$$

first suggested by Kuzmin.[2] The proposed experiment will require about 50 tons of Ga.

The neutrino capture cross sections for solar neutrinos incident on ^{71}Ga are given in Table I for ground-state to ground-state transitions. We present cross sections for all the important sources of solar neutrinos and also for ^{65}Zn (which can be used as a terrestrial neutrino source[3] to verify the overall validity of the proposed experiment). The cross sections have been calculated accurately by the standard methods.[4-7]

The predicted capture rates for various extreme assumptions about the solar interior or neutrino propagation are shown in Table II. The first five models listed in Table II are concerned only with aspects of the solar interior and they are as follows: (1) a standard solar model[8]; (2) a model in which the only neutrinos come from the basic, low-energy reactions ($p+p \to {}^2\text{H}+e^+ + \nu_e$ and $p+e^- + p \to {}^2\text{H}+\nu_e$); (3) a model in which the solar interior is depleted of heavy elements[8]; (4) a model in which the composition of the sun is completely homogenized for its entire lifetime[9]; and (5) an extreme model in which the central temperature of the sun is so high that all of the nuclear energy is produced by the CNO cycle. The standard solar model and the CNO model are inconsistent with the ^{37}Cl experiment. The *p-p*, low–heavy-elements, and complete-mixing models are consistent with the ^{37}Cl experiment, but are apparently inconsistent with other aspects of the theory or observation of stellar evolution. The adoption of any of the nonstandard models would have important implications for many branches of astronomy and cosmology via the dating of old stars or the inferred helium abundance.

The first four models shown in Table II all give about the same capture rate [80 ± 10 SNU (solar neutrino units)] since they are primarily sensitive to the low-energy *p-p* (and *pep*) neutrinos ($\geq 70\%$ of the capture rate would come from these basic reactions). The *p-p* (and *pep*) neutrino fluxes are practically invariant to parameter

TABLE I. Neutrino absorption cross sections[a] for ^{71}Ga. Also given are the products of flux and cross section for a standard solar model in solar neutrino units (1 SNU = 10^{-36} captures per target atom per sec).

Source	Cross section[b] (10^{-46} cm^2)	Flux × (cross section) (Standard model; SNU)
p-p	10.7	65
pep	157	2
^{7}Be	64	21
^{8}B	3×10^3	1
^{13}N	53	1
^{15}O	92	2
^{65}Zn	67	...

[a]These are cross sections for transitions to the ^{71}Ge ground state only; they have uncertainties of $\leq 5\%$. The contributions of transitions to excited states are small (cf. Ref. 5).

[b]The cross sections are given per reaction (for *p-p* and *pep*) or per decay (for the radioactive sources).

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TABLE II. Predicted capture rates for some extreme hypotheses.

Model	Predicted capture rate[a] (SNU)	Tons of Ga for 1 capture/day
Standard sun	92	37
Only *p-p* and *pep*	71	47
Heavy elements depleted	79	43
Homogenized sun	82	41
CNO	487	7
Neutrino oscillations	$\leqslant 31$	$\geqslant 110$
Neutrino decay	0	∞

[a]The uncertainties in these rates due to uncertainties in the cross sections are $\leqslant 10\%$ except for the pure CNO model (cf. Ref. 5).

changes since, if the sun is currently supplying its luminosity by nuclear fusion via the *p-p* cycle of reactions, then the *p-p* (and *pep*) fluxes are a direct measure of the sun's luminosity.

The last two rows of Table II refer to situations in which the standard theory of weak interactions has been modified to include either neutrino oscillations[10] or neutrino decay.[11] They give much lower predicted rates than any of the listed astronomical hypotheses. The effect of neutrino oscillations, when averaged over the solar neutrino spectrum,[12] yields a reduction factor, R_{osc}, that is the same for all experiments. Comparison of the predictions for the ^{37}Cl experiment with observations[1] yields the value of $R_{osc} \leqslant \frac{1}{3}$ used in row 6 of Table II. Note, in connection with row 7, that if the higher-energy neutrinos that are most important in the ^{37}Cl experiment decay on their way to the earth, then certainly the lower-energy *p-p* (and *pep*) neutrinos also decay. A counting rate below 70 SNU could also arise, in principle, if the sun is now in an abnormal phase in which its nuclear energy generation rate is much less than its surface luminosity.[13] However, for most of the models that are in the literature,[14] the reduction in the counting rate would not be nearly as great as for either the oscillation or decay hypotheses. Moreover, these latter two processes give specific predictions for the gallium experiment when combined with the ^{37}Cl experiment.

We conclude that, if a ^{71}Ga experiment gave a result in the range of 70–90 SNU, neutrino decay or oscillations over a distance of 1 AU could be ruled out, putting the burden of explaining the low result for ^{37}Cl squarely on the astrophysicists; on the other hand, a ^{71}Ga result at about one-third that level or lower would be evidence for neutrino oscillations, and a zero result would indicate neutrino decay.

We note, from the last column of Table II, that an experiment with enough sensitivity to detect the *p-p* and *pep* neutrinos would require about 50 tons of gallium.[15] The half-life of ^{71}Ge is 11.8 days, so that production of one ^{71}Ge atom per day leads to a steady-state amount of about seventeen ^{71}Ge atoms. Thus a procedure for quantitative and reliable isolation of a few atoms of ^{71}Ge from 50 tons of gallium and for their subsequent purification and counting is required. We have developed suitable procedures for the separation of Ge from two different forms of target: an acidified 8*M* $GaCl_3$ solution and gallium metal.

From a $GaCl_3$ solution the germanium can be swept out as $GeCl_4$ by a He purge at about 60°C. From a metallic Ga target the germanium, even when carrier-free, can be separated by contacting the liquid Ga with an acid solution that contains an oxidizing agent such as H_2O_2. Since a heterogeneous system is involved, a large surface area must be provided. Conditions were found for forming, for a definite and controlled time, a finely divided dispersion of liquid gallium metal in weakly acidic aqueous phase. At the end of the allocated interval of time the dispersion breaks down spontaneously and cleanly into two phases which can be separated readily, and the germanium, along with a small amount ($\leqslant 0.2\%$) of the gallium, is found in the aqueous phase. The whole process can be adjusted to take a few minutes. After addition of HCl, the germanium can be swept out of the aqueous solution as $GeCl_4$ by a stream of He. The ensuing treatment in both procedures is the same: $GeCl_4$ is trapped in an alkaline solution and then reduced to germane (GeH_4) with sodium borohydride. Finally, germane is purified by gas chromatography and introduced with argon into a small proportional counter. The techniques developed for ^{37}Ar measurements,[1] including pulse-height and rise-time discrimination, are directly applicable to ^{71}Ge counting. The chemical yield of the procedure is determined by measuring the volume of GeH_4 obtained in relation to the amount of Ge carrier added initially (about 1 mg).

The chemical separation using a $GaCl_3$ target is most appealing because of its simplicity, elegance, and well-understood chemistry; however, since practically all gallium is produced and commercially used in the form of the metal, economic considerations favor a metallic Ga target. We have tested both of the chemical schemes many times on amounts of gallium up to 20 kg with germanium recoveries of 90% or better, and we anticipate no difficulties in scaling each up to full scale. Quantitative recovery of carrier-free trace quantities of ^{69,71}Ge introduced into Ga metal by (p,n) reactions has been demonstrated.

An extractor for 200 kg is being designed as a pilot model for the ultimate extractor of 1–2-ton capacity. The procedure for the extraction of Ge from a large experiment (50 ton Ga) is envisaged to involve semicontinuous batch processing of 1–2 tons at a time. The whole operation from the extraction to the counter filling should take about a day.

An interfering reaction in all radiochemical neutrino detectors is the (p,n) reaction on the target material which gives the same product as neutrino capture. The major sources of protons in a deep-mine experiment are muon interactions, (α,p) reactions from natural α emitters, and (n,p) reactions from fast neutrons originating in the rock wall. This last source can be eliminated by water shielding as is done in the ^{37}Cl experiment. A unique advantage in the Ga system is that ^{69}Ge ($t_{1/2}=39$ h) is also produced by these interfering (p,n) reactions but not by low-energy neutrinos. The activity of ^{69}Ge observed may thus be used to monitor the effectiveness of the various measures taken to eliminate background reactions. Furthermore, ^{72}As (26 h) and ^{74}As (17.8 day) are produced in Ga by α particles originating from Th and U via direct (α,n) reactions and are, therefore, made in much higher yield than the secondary product ^{71}Ge. The Ga system possesses, therefore, the unique feature of being self-monitoring and providing its own corrections independent of any other measurements if ^{69}Ge, ^{72}As, and ^{74}As yields are measured along with ^{71}Ge. Fortunately the chemical procedure described results in the removal of As along with Ge. After volatilization of GeH_4 and AsH_3, the two are separated by gas chromatography.

We have measured the cross sections for ^{69}Ge and ^{71}Ge production in Ga and in $8M$ $GaCl_3$ and for ^{37}Ar production in C_2Cl_4 with 225-GeV muons at Fermilab. They are, respectively, 30 ± 3 and 8 ± 1 μb per Ga atom in $8M$ $GaCl_3$, 64 ± 5 and 16 ± 2 μb in Ga metal, and 5.3 ± 0.5 μb per Cl atom in C_2Cl_4. Using the cosmic-ray–induced ^{37}Ar production rate[16] of 0.080 ± 0.024 atoms/day in 610 tons of C_2Cl_4 in the Homestake Mine experiment [depth 4400 hg/cm^2 (1 hg $=10^2$ g), average muon energy 320 GeV], we estimate the production rates for ^{69}Ge and ^{71}Ge in 50 tons of Ga at the same depth to be 0.022 ± 0.007 and 0.006 ± 0.002 atoms/day in $8M$ $GaCl_3$ and 0.047 ± 0.016 and 0.012 ± 0.004 atoms/day in Ga metal. Thus the muon-induced ^{71}Ge will be negligible in the proposed experiment; furthermore, the larger ^{69}Ge production makes it possible, at least in principle, to distinguish between muon and neutrino signals.

We have also measured yield curves for the production, in gallium, of ^{69}Ge, ^{71}Ge, ^{72}As, and ^{74}As by α particles in the range of interest (4–11 MeV). The results show that 0.7 g of Th in equilibrium with its daughters or 0.05 μg of ^{226}Ra will produce 0.1 ^{71}Ge atoms per day in a metallic Ga target. The tank walls and Ga metal must therefore be free of α emitters down to about these levels. However, verification that these impurity specifications have been met can be obtained from the monitoring reactions mentioned; e.g., the α particles of the ^{232}Th chain will produce about 35 times as many atoms of ^{74}As as of ^{71}Ge, so that ^{74}As will be readily detectable via its electron-capture branch at any α level that requires a significant ^{71}Ge correction. Although ^{71}Ge can be produced from Zn impurity by (α,n) reaction on ^{68}Zn, the effect of Zn was shown to be entirely negligible for all reasonable levels of this impurity. Furthermore, the production of ^{69}Ge by ^{66}Zn(α,n) again serves as an internal monitor.

The conclusion from all these considerations is that a ^{71}Ga detector for low-energy solar neutrinos is feasible and desirable.

We are grateful to many colleagues for advice, suggestions, and constructive criticism. This work was supported by the Office of Energy Research of the U. S. Department of Energy and by the National Science Foundation.

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[5]J. N. Bahcall, to be published. Three excited states of ^{71}Ge at excitation energies of 0.175 MeV ($J=\frac{5}{2}^-$), 0.50 MeV ($J=\frac{3}{2}^-$), and 0.71 MeV ($J=\frac{3}{2}^-$) must be considered in determining solar-neutrino absorption cross sections. From experimental information on seventeen β-decay transitions with approximately the same shell-model description as the transitions of interest, one can estimate the maximum effect of these excited states by making the extreme assumption that each of the transitions to excited states of ^{71}Ge occurs at the *fastest* rate exhibited by an analogous transition in the available experimental data. This assumption leads to capture rates < 7% above those in Table II for all the cases considered except for the very high-counting example of CNO (where the increase is 28%).

[6]Transitions to the analog state of ^{71}Ge do not contribute to the formation of ^{71}Ge(g.s.) since the analog state is particle unstable. The average cross section for the reaction $\nu_e + {}^{71}\mathrm{Ga} \rightarrow {}^{70}\mathrm{Ge}\ ({}^{70}\mathrm{Ga}) + n\ (p) + e^-$ is, for ^{8}B neutrinos, 4×10^{-43} cm^2.

[7]The results given here, and in more detail in Ref. 5, are in good agreement with the independent results of G. Domogatski, Yad. Fiz. 25, 1125 (1977). His results are typically 5% larger than those given here (presumably because of less numerical precision in the calculation of Fermi functions and the ft value) except for ^{8}B (where our value is 25% larger than his). Domogatski did not report the ^{65}Zn cross section nor did he consider the effect of excited states.

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[15]Since the gallium will undoubtedly be acquired over a period of several years, exposures will first be made with smaller quantities. We note that a 7-ton experiment will serve the useful purpose of verifying the conclusion, already indicated by the ^{37}Cl experiment, that the sun is not currently generating its luminosity by the CNO cycle of reactions.

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