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Abstract

The reported counting rates of the SAGE and GALLEX solar neutrino detectors have been used to establish an improved limit on the charge non-conserving decay $^{71}Ga \rightarrow {}^{71}Ge$ + neutrals. The 1σ lower limit on the lifetime against such decays is 3.5×10^{26} years. This result can be used to establish a 1σ upper limit on the ratio of the charge-nonconserving to the normal weak interaction decay width of the neutron, $\Gamma(n \rightarrow p + \nu_e + \overline{\nu}_e)/\Gamma(n \rightarrow p + e^- + \overline{\nu}_e) \leq 8\times10^{-27}$. This result represents by far the most stringent limit yet derived for charge non-conserving decays involving baryons.

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Radiochemical solar neutrino experiments, such as the pioneering ^{37}Cl-based experiment of Davis and his collaborators[1] and the more recent SAGE[2] and GALLEX[3] ^{71}Ga-based experiments, make use of the fact that the capture of electron-type neutrinos on such target nuclei produce radioactive nuclei (^{37}Ar and ^{71}Ge, respectively) which can be chemically separated and counted off line. In order to reduce the possibility of the same radioactive nuclei being produced by other processes, such as cosmic-ray interactions, these experiments are performed deep underground where the cosmic-ray flux is greatly attenuated. While these radiochemical experiments on their own cannot definitively prove that the ^{37}Ar and ^{71}Ge atoms that are detected were produced by solar neutrino interactions, when combined with theoretical estimates[4-9] for expected capture rates on these targets and with the results of the direct real-time Kamiokande water Cerenkov experiment[10], it has been generally concluded that solar neutrino interactions are the most likely production mechanism.

For some radiochemical solar neutrino experiments, there is another process by which the same product nuclei can be made. Figure 1 illustrates the situation for ^{71}Ga and ^{71}Ge. Figure 1(a) shows the ν_e capture reaction on ^{71}Ga producing ^{71}Ge in its ground and low-lying excited states and also the normal electron-capture decay of ^{71}Ge back to ^{71}Ga. The Q-value for this electron capture decay is 235.7 keV[11]. Thus it is not energetically possible for ^{71}Ga to undergo a normal β^- decay to ^{71}Ge. However, as was first pointed out by Feinberg and Goldhaber[12], because there is no electron emitted, a charge non-conserving (CNC) process such as $n \rightarrow p + \gamma$ or $n \rightarrow p + \nu_e + \overline{\nu}_e$ provides 511 keV more decay energy than does a charge conserving beta decay. The Q-value for such a CNC decay from the ^{71}Ga ground state to the ^{71}Ge ground state is 275.3 keV. Thus as is illustrated in Figure 1(b), it is possible, at least in principle, for ^{71}Ga to undergo CNC decays to both the ground state and first excited state of ^{71}Ge. While the conservation of electric charge is thought to be an *absolute* conservation law, " ... the basic principles of theoretical physics cannot be accepted *a priori*, no matter how convincing they may seem, but rather must be justified on the basis of relevant experiments."[12] Thus, it seems worthwhile to make use of recent developments in the SAGE and GALLEX experiments to derive improved limits on such CNC decays.

As discussed by Bahcall[13,14], one cannot tell from a radiochemical gallium experiment alone whether solar neutrino-induced reactions or charge non-conserving neutron decays are responsible for the appearance of ^{71}Ge atoms in a target of ^{71}Ga. This is not the case for the Davis experiment because the ^{37}Ar-^{37}Cl mass difference is too large to allow the CNC decay of ^{37}Cl to ^{37}Ar. However, as also discussed by Bahcall, the likelihood of charge non-conserving effects to be just large enough to be comparable to what is expected from solar neutrino reactions seems remote. Furthermore, future real-time direct counting experiments, such as the proposed liquid scintillator-based Borexino detector[15] and the proposed liquid helium-based HERON detector[16], are not sensitive to charge non-conserving processes, but like the ^{71}Ga experiment, will be sensitive to p-p and ^{7}Be solar neutrinos. Thus, by comparing the counting rates from these experiments one could decide if CNC effects were contributing to the ^{71}Ga signal.

The SAGE[2] and GALLEX[3] collaborations have reported results of 73 ± 18 and 79 ± 12 SNU, respectively, where 1 SNU = 10^{-36} neutrino captures (or CNC decays) per target atom per second. Furthermore, the GALLEX collaboration has recently reported the results of a calibration of their detector performed with an intense ^{51}Cr neutrino source.[17] This test showed, among other things, that the ^{71}Ge chemical separation and recovery efficiency for the GALLEX experiment is essentially 100%. Combining the SAGE and GALLEX results, one concludes that the counting rate for such a radiochemical gallium detector is less than or equal to 90 SNU (1σ). Thus, the rate for the CNC decay of ^{71}Ga to ^{71}Ge can be no larger than this.

$$dN(^{71}Ga)/dt = \lambda_{CNC}\, N(^{71}Ga) < 10^{-36}\, P\, N(^{71}Ga)/s \qquad (1),$$

where $N(^{71}Ga)$ is the number of ^{71}Ga atoms in the solar neutrino detector, λ_{CNC} = CNC decay rate of ^{71}Ga, and P is the upper limit (in SNU) on the counting rate of the gallium solar neutrino detectors. Thus,

$$\tau_{CNC} \geq 10^{36}\ s/P = 3.17 \times 10^{28}\ y\ /P \qquad (2).$$

Inserting the 1σ upper limit of 90 SNU from the SAGE and GALLEX experiments into Eqn. 2, we find

$$\tau_{CNC}\,(^{71}Ga \rightarrow {}^{71}Ge) \geq 3.5\times10^{26} \text{ years.} \qquad (3)$$

As pointed out by Bahcall[13], if one assumes that the weak interaction contains a small CNC component in which a neutrino replaces the electron in the lepton current, then one can convert a limit on τ_{CNC} into a limit on the ratio of neutron decay branching ratios. Bahcall finds

$$\frac{\Gamma(n \rightarrow p + \nu_e + \overline{\nu}_e)}{\Gamma(n \rightarrow p + e^- + \overline{\nu}_e)} = \frac{\tau(n)}{\tau_{CNC}} \left[W(n) / W(^{71}Ga) \right]^5 \left[ft\,(^{71}Ga) / ft\,(n) \right] \qquad (4),$$

where $\tau(n)$ is the neutron lifetime (887 s), W(n) is the mass difference between a neutron and a proton (1.293 MeV), and the comapartive half-life ft (n) = 1042 s (Ref. 18). The partial lifetime for a CNC decay from the ^{71}Ga ground state to the ^{71}Ge ground state is obviously greater than or equal to the limit on the total CNC lifetime derived above. Thus, we can derive a conservative limit on the CNC decay width of the neutron by considering only the ground-state to ground-state transition. For this decay mode, W(^{71}Ga) is the nuclear mass difference between the ^{71}Ga and ^{71}Ge ground states (0.275 MeV) , τ_{CNC} is the lifetime for charge nonconservation derived above, and the comparative half life derived from the electron capture decay of ^{71}Ge has been corrected for the statistical factor (2J + 1) / (2J' + 1) that takes into account the difference in spin between the initial and final nuclear states: ft (^{71}Ga) = 45085 s (Ref. 11). Inserting these values into Eqn. 4 yields the 1σ upper limit

$$\frac{\Gamma(n \rightarrow p + \nu_e + \overline{\nu}_e)}{\Gamma(n \rightarrow p + e^- + \overline{\nu}_e)} \leq 8\times10^{-27}. \qquad (5)$$

Previous searches for this CNC decay mode of the neutron have been performed using ^{87}Rb (Refs. 19,20,21), ^{71}Ga (Ref. 22), ^{113}Cd (Ref. 23), and ^{127}I (Refs. 24,25). The most stringent of the published limits on this CNC process of which we are aware came from the work of Barabanov *et al.*[22] who were developing the radiochemistry for the SAGE experiment. Using a 300 kg sample of gallium located at a depth of 20 meters of water equivalent, they obtained a limit of

$$\frac{\Gamma(n \rightarrow p + \nu_e + \overline{\nu_e})}{\Gamma(n \rightarrow p + e^- + \overline{\nu_e})} \leq 9 \times 10^{-24}. \tag{6}$$

Thus, the present result represents more than a thousand-fold improvement on the limit for the charge nonconserving decay of the neutron. If future direct counting experiments are able to determine the flux of p-p and ^{7}Be neutrinos reaching the Earth from the Sun, then this limit could be improved by subtracting the "solar neutrino background" from the observed counting rates of the SAGE and GALLEX experiments.

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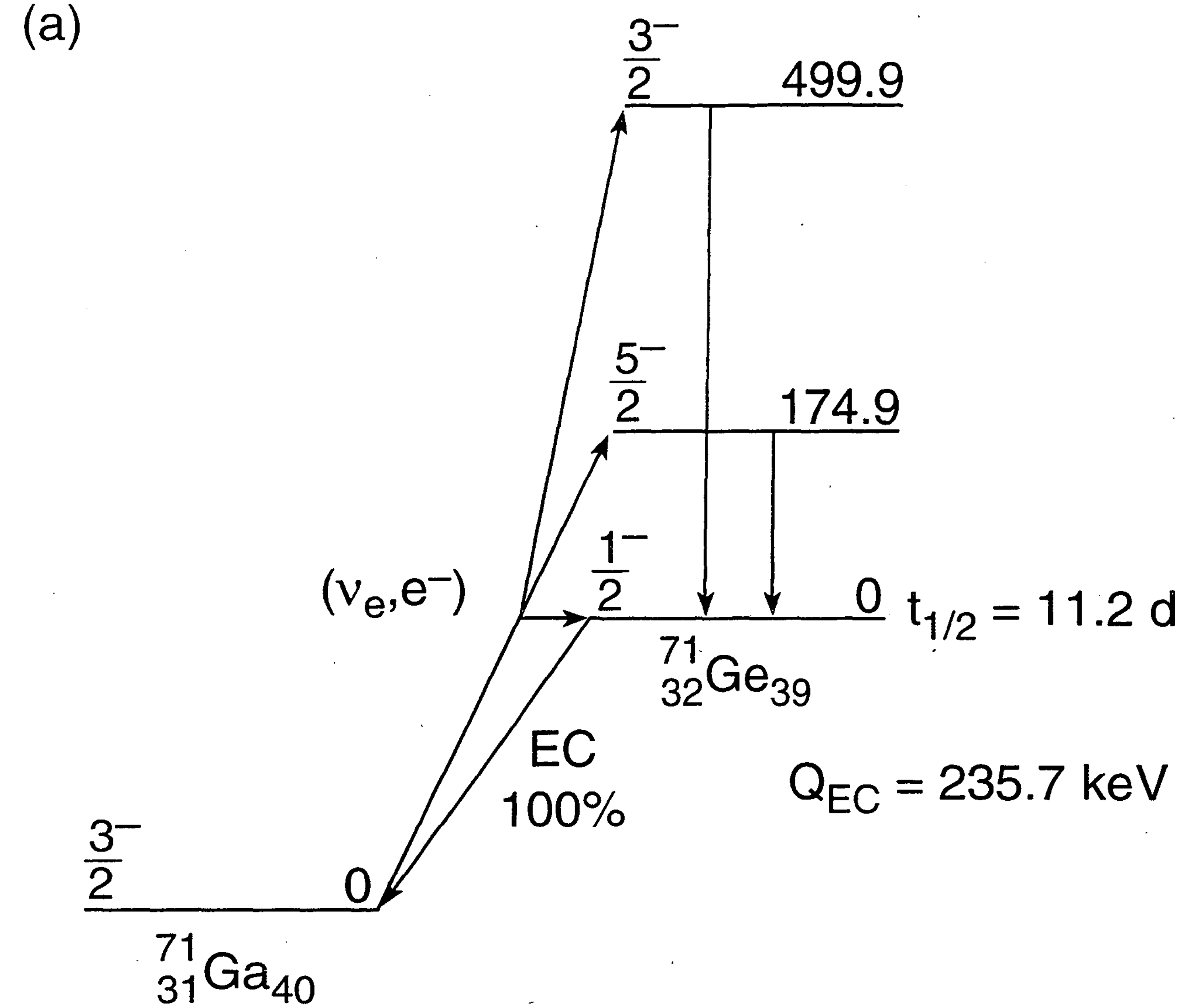
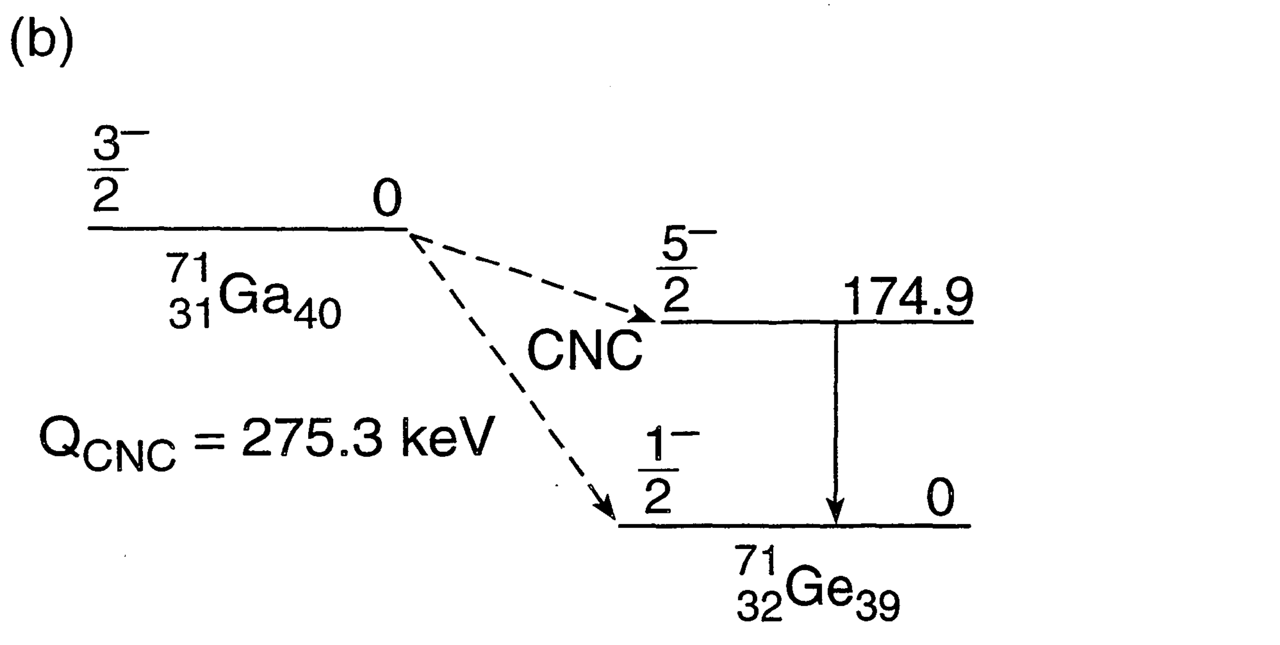
Figure Caption

1. Partial level schemes for ^{71}Ga and ^{71}Ge illustrating (a) the solar neutrino reaction which produces ^{71}Ge from ^{71}Ga and the normal electron-capture decay of ^{71}Ge to ^{71}Ga and (b) the charge non-conserving decay of ^{71}Ga to ^{71}Ge. All energies are given in keV.





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