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^{37}Ar as a calibration source for solar neutrino detectors

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I discuss the possibility that a high-intensity 811-keV ^{37}Ar neutrino source, produced by neutron capture on separated ^{36}Ar, could be used to calibrate the ^{7}Be solar neutrino capture cross sections of ^{71}Ga, ^{127}I, and other detectors.

Calibration tests of solar neutrino detectors are important both to verify detector efficiencies and to eliminate uncertainties in nuclear cross sections.[1] Several calibration sources have been discussed previously[2-4]

$$e^- + {}^{65}\mathrm{Zn} \rightarrow \begin{cases} {}^{65}\mathrm{Cu} + \nu(1.343\ \mathrm{MeV}, 47.8\%), \\ {}^{65}\mathrm{Cu}^* + \nu(0.227\ \mathrm{MeV}, 50.75\%), \end{cases} \quad \tau_{1/2} = 244.1\ \mathrm{d},$$

$$e^- + {}^{51}\mathrm{Cr} \rightarrow \begin{cases} {}^{51}\mathrm{V} + \nu(0.746\ \mathrm{MeV}, 90.1\%), \\ {}^{51}\mathrm{V}^* + \nu(0.426\ \mathrm{MeV}, 9.9\%), \end{cases} \quad \tau_{1/2} = 27.7\ \mathrm{d},$$

$$e^- + {}^{152}\mathrm{Eu} \rightarrow \begin{cases} {}^{152}\mathrm{Sm}^* + \nu(1.048\ \mathrm{MeV}, 1.3\%), \\ {}^{152}\mathrm{Sm}^* + \nu(0.772\ \mathrm{MeV}, 22\%), \\ {}^{152}\mathrm{Sm}^* + \nu(0.624\ \mathrm{MeV}, 17\%), \\ {}^{152}\mathrm{Sm}^* + \nu(0.328\ \mathrm{MeV}, 25\%), \\ {}^{152}\mathrm{Sm}^* + \nu(0.278\ \mathrm{MeV}, 2.2\%), \end{cases} \quad \tau_{1/2} = 13\ \mathrm{yr}.$$

The discrete energies of the emitted neutrinos and the corresponding branching ratios are given in parentheses. In particular, the Gallex collaboration plans to use an intense ($\sim$1 MCi) ^{51}Cr source to calibrate the ^{71}Ga experiment:[5] the 746-keV neutrino will excite all three Gamow-Teller transitions [to the $\frac{1}{2}^-$ ground (E_{ex}=236 keV), $\frac{5}{2}^-$ (E_{ex}=411 keV), and $\frac{3}{2}^-$ (E_{ex}=736 keV) states in ^{71}Ge] that contribute to the capture of ^{7}Be solar neutrinos (E_ν=862 keV).

The original motivation for the work reported here was the observation that none of the above sources could provide an unambiguous calibration of the ^{7}Be neutrino cross section for the proposed ^{127}I detector.[6] The transition excited by ^{7}Be neutrinos, to the $\frac{1}{2}^+$ state lying at 125 keV in ^{127}Xe, has an excitation threshold of 789 keV. Thus the ^{51}Cr neutrinos and the principle ^{152}Eu neutrinos are too low in energy. The 1.343-MeV neutrinos from ^{65}Zn are too energetic, exciting several additional Gamow-Teller (GT) transitions.[7] While the ^{127}I experiment is very attractive technically and potentially inexpensive, uncertainties in estimating the ^{7}Be and ^{8}B neutrino absorption cross sections are a concern. Thus, a calibration of the transition to the $\frac{1}{2}^+$ level is very important: in addition to determining the ^{7}Be cross section, it could provide a normalization for (p,n) mappings of the GT strength. The normalization is a primary uncertainty in (p,n) calibrations of ^{8}B neutrino cross sections.[8]

A search of the table of isotopes revealed one practical calibration source for the ^{127}I experiment, ^{37}Ar ($\tau_{1/2}$=35 d). Several properties of this nucleus are also very attractive from the perspective of a ^{71}Ga calibration, so the discussion below will concentrate on the general attributes of ^{37}Ar as a neutrino source.

Neutrino yield. ^{37}Ar decays exclusively to the ground state of ^{37}Cl, generating a monoenergetic neutrino with E_ν=811 keV. (More correctly, this is the K-capture neutrino energy. L capture occurs with a 10% probability, yielding a neutrino with E_ν=814 keV.) Thus, in contrast to ^{65}Zn, ^{51}Cr, and ^{152}Eu, no energetic nuclear γ rays are produced, greatly lessening safety concerns, as discussed below. Because of the higher neutrino energy and the 100% branching ratio to the ^{37}Cl ground state, the cross section for exciting nuclear targets exceeds that for ^{51}Cr. Comparative results for the relevant states in ^{71}Ge (Table I) show that the ^{37}Ar neutrino cross section is 20% to 44% larger. In addition, the longer half-life of ^{37}Ar provides 26% more neutrinos. The net result, in the case of ^{71}Ga, is that a 1-MCi ^{37}Ar source is equivalent to 1.5 MCi (1.8 MCi) of ^{51}Cr for exciting the ground state (500 keV state) in ^{71}Ge.

TABLE I. Neutrino cross sections for exciting states in ^{71}Ge and ^{127}Xe by ^{51}Cr, ^{37}Ar, and ^{7}Be neutrinos, taking $|M^2|=1$ for all transitions. The units are 10^{-44} cm^2.

Source	^{71}Ge (g.s.)	^{71}Ge (175 keV)	^{71}Ge (500 keV)	^{127}Xe (125 keV)
^{51}Cr	3.88	2.59	0.85	0.0
^{37}Ar	4.66	3.24	1.22	3.25
^{7}Be	4.75	3.25	1.33	3.41

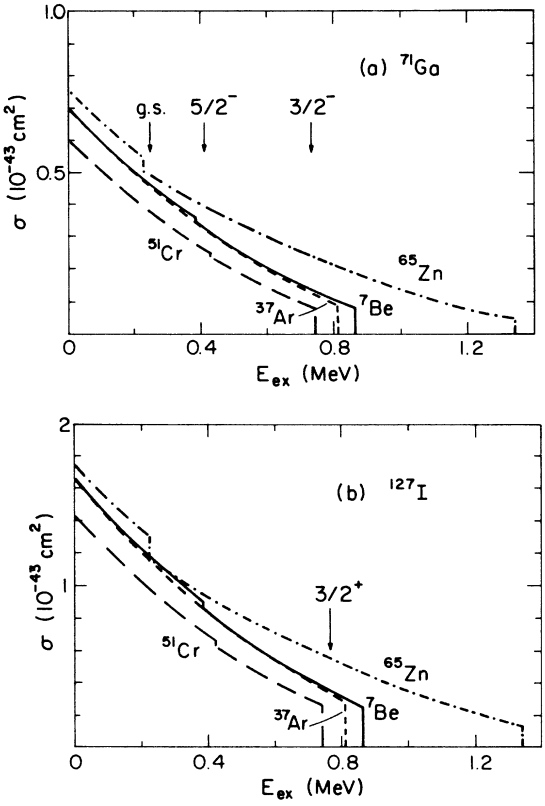

FIG. 1. Neutrino cross sections in (a) ^{71}Ga and (b) ^{127}I as functions of the atomic excitation energy for various neutrino sources, assuming a fixed nuclear matrix element $|M^2| = 1$.

In Fig. 1, cross sections for ^{7}Be, ^{37}Ar, ^{51}Cr, and ^{65}Zn neutrinos, assuming a fixed nuclear matrix element $|M^2| = 1$, are shown as a function of the atomic excitation energy E_{ex}. Note that the ^{37}Ar neutrino cross section tracks that for ^{7}Be solar neutrinos remarkably well, both absolutely and relatively. The latter is important, when, as in the case of ^{71}Ga, more than one nuclear transition contributes. The ^{37}Ar/^{7}Be and ^{51}Cr/^{7}Be cross section ratios are 0.96 ± 0.04 and 0.73 ± 0.09 over the ^{7}Be neutrino excitation range for ^{71}Ga (236 keV $\leq E_{ex} \leq$ 736 keV). Thus, an ^{37}Ar source mimics the ^{7}Be solar neutrino phase space a factor of three more accurately than does a ^{51}Cr source.

Production of ^{36}Ar. ^{37}Ar can be produced by irradiating enriched ^{36}Ar (natural abundance 0.337%) in the intense neutron flux of a reactor. The relevant data on Ar isotopes are given in Table II. The ^{36}Ar(n,γ) cross section of $\sigma = 5.2 \pm 0.5$ b is almost an order of magnitude

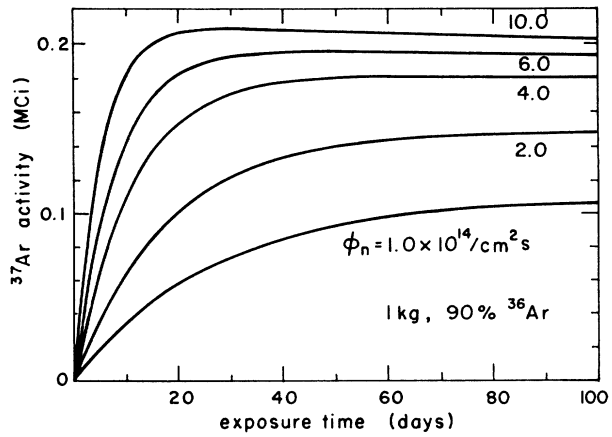

FIG. 2. The ^{37}Ar activity as a function of irradiation time for various values of the neutron flux ϕ_n.

larger than that for ^{40}Ar, the principal stable isotope. Thus, any enrichment above 10% makes ^{36}Ar the primary neutron absorber.

The very large (n,α) and (n,p) cross sections for ^{37}Ar, 1970 and 69 b, lead to unfortunate "burn-up" problems[9] for the product isotope, limiting the achievable ^{37}Ar/^{36}Ar ratio to no more than 0.0025. This limit is equivalent to a maximum activity of 0.23 MCi for a 1-kg target, assuming a ^{36}Ar content of 90%. The most straightforward solution to this problem, irradiating 5–10 kg of ^{36}Ar to produce a $\sim$1-MCi source, appears to be practical, as discussed below. However, if the burn-up problem could be overcome, a 1-MCi source could be generated from as little as 0.6 kg of ^{36}Ar (assuming a neutron intensity of $\phi_n \sim 10^{15}$/cm^{2}s for the resulting compact target). Thus, it might be profitable to explore recirculation systems for removing ^{37}Ar during irradiation, or the feasibility of extracting ^{37}Ar between a series of short, intense irradiations. Alternatively, one might explore whether the ^{36}Ar(n,γ)/^{37}Ar(n,γ) ratio is more favorable at nonthermal energies, such as those available at "fast flux" reactors. Although ^{37}Ar can also be produced by ^{40}Ca(n,α), the thermal neutron cross section is very small $(2.5 \pm 1.1$ mb) because of the unfavorable Q value (1.75 MeV). Thus, this option would require an intense, energetic neutron source.

The most likely strategy is to use a larger ^{36}Ar target to compensate for the burn-up problem. In Fig. 2, the ^{37}Ar activity is plotted as a function of exposure time for a 1-kg target containing 90% ^{36}Ar, 5% ^{38}Ar, and 5% ^{40}Ar. The activity calculations coupled all the isotopes in Table I, the ^{37}Ar(n,p) and (n,α) products ^{37}Cl and ^{34}S, and their

TABLE II. Abundances, half-lives, and thermal neutron capture cross sections (Ref. 14) for argon isotopes.

	^{36}Ar	^{37}Ar	^{38}Ar	^{39}Ar	^{40}Ar	^{41}Ar	^{42}Ar
Abundance	0.337	. . .	0.063	. . .	99.60	. . .	. . .
σ_n^* (b)	5.2 ± 0.5	2040 ± 340	0.8 ± 0.2	600 ± 300	0.66 ± 0.01	0.5 ± 0.1	?
$\tau_{1/2}$	. . .	35 d	. . .	269 yr	. . .	1.83 h	33 yr

*These are (n,γ) cross sections except for ^{37}Ar, where $\sigma_n \simeq \sigma(n,p) + \sigma(n,\alpha) = (69 \pm 14$ b$) + (1970 \pm 330$ b).

(n,γ) daughters ^{38}Cl and ^{35}S. For a 40-d exposure, an activity of 0.178 MCi is achieved with a neutron flux of 4×10^{14}/cm^{2}s. As this activity is 75% of the theoretical maximum, higher fluxes, even if attainable, would not be of significant benefit. Reducing ϕ_n by a factor of four (to 10^{14}/cm^{2}s) halves the activity (0.086 MCi). For definiteness, in the calculations below I assume $\phi_n=2\times10^{14}$/cm^{2}s, yielding an activity of 0.134 MCi. Thus, 7.5 kg of target (90% ^{36}Ar) would yield a 1-MCi source after 40 d of irradiation.

At 0 °C and one atmosphere of pressure the density of argon is 1.78 g/ℓ. At −189.4 °C argon liquefies, with the fluid density being 1.40 kg/ℓ. This places a lower bound on the dimensions of the source. At liquid density the neutron absorption length in enriched argon (90% ^{36}Ar) is 9.1 cm, a value that will drop to 5.8 cm at the end of the 40-d irradiation described above. To keep the target relatively transparent to neutrons, a maximum thickness of about 3 cm is then appropriate. Thus, the minimum dimensions of a 7.5-kg target are 3 cm×(40 cm)^2. It may prove possible to irradiate a liquid target, despite the engineering problems this presents. Alternatively, a highly compressed gas could be used both in the irradiation and calibration phases. Since densities approaching those of a liquid are achievable, no large increase in target dimensions should result.

An argon source is attractive because gas diffusion, distillation, and other technologies exist for separating ^{36}Ar. For instance the 213-m cryogenic distillation column operated by Los Alamos National Laboratory can produce about 12 kg of ^{36}Ar in 2.5 yr of operation.[10] Production costs are modest, and enrichments in excess of 90% can likely be achieved (e.g., 92% ^{36}Ar, 4% ^{38}Ar, and 4% ^{40}Ar).[10] The production of such quantities of ^{36}Ar could be of value to the ^{71}Ga, ^{127}I, and other future experiments[11,12] (e.g., ^{81}Br, ^{115}In): as very little of the ^{36}Ar is depleted by the irradiation, sources could be recycled.

Safety aspects. The absence of a nuclear gamma ray accompanying the decay of ^{37}Ar is important from the standpoint of safety. While the 320-keV γ emitted in ^{51}Cr decay can be fully shielded by about 2 cm of lead,[13] the possibility of a rupture in the containment vessel must be a constant concern in transporting the source from the reactor to the underground laboratory, and in handling at the laboratory. The ^{37}Ar decay is accompanied only by x rays emitted in atomic rearrangement: the K-electron binding energy is 3.21 keV.

The principal concern among other isotopes of argon is the production of ^{41}Ar ($\tau_{1/2}=1.83$ h) from ^{40}Ar. The activity in ^{41}Ar will be maintained at ~22 kCi during irradiation, assuming that $\phi_n=2\times10^{14}$/cm^{2}s and that the 7.5-kg target contains 5% ^{40}Ar. (The ^{41}Ar activity varies as the product of the ^{40}Ar content and ϕ_n.) The dominant ^{41}Ar β^- decay branch (99.2%) emits electrons with kinetic energies up to 1.2 MeV. With the short half-life, this activity can be allowed to decay away before the source is moved from the reactor site. If the target contains 5% ^{38}Ar, the activity in long-lived ^{39}Ar ($t_{1/2}=269$ yr) is much lower (6.2 Ci). The β^- decay of ^{39}Ar produces electrons with energies up to 565 keV.

The corresponding activity from ^{38}Cl ($\tau_{1/2}=37.3$ min), produced by ^{37}Ar$(n,p)^{37}$Cl followed by ^{37}Cl$(n,\gamma)^{38}$Cl ($\sigma_{n\gamma}=0.43$ b), is ~210 Ci after the 40-d irradiation. The decay to the ground state of ^{38}Ar is strong (58% branch) and produces high-energy electrons ($\lesssim$4.92 MeV). It is again fortunate that this activity is short-lived. The activity from ^{35}S ($\tau_{1/2}=87.4$ d), produced by ^{37}Ar$(n,\alpha)^{34}$S followed by ^{34}S$(n,\alpha)^{35}$S ($\sigma_{n\gamma}=0.23$ b), is low (20 Ci) and produces only low-energy electrons ($\lesssim$168 keV).

Because the target is a gas, its purity should be unusually high, minimizing concerns about high-energy γ's emitted from irradiated trace elements. Radioactivity from the vessel containing the argon would have to be studied.

Summary. It appears that ^{37}Ar could provide an unusually safe and intense neutrino source. The economics may be quite favorable because highly enriched ^{36}Ar can be produced in multikilogram quantities at existing facilities. As the ^{37}Ar neutrinos mimic the ^{7}Be solar neutrino phase space remarkably well, this source could be used to measure the ^{7}Be neutrino cross sections for targets like ^{71}Ga, ^{81}Br, and ^{115}In. In the case of ^{127}I, where the ^{7}Be neutrino transition has a high threshold, ^{37}Ar appears to be unique as a potential calibration source. Thus, from a theoretical viewpoint, a ^{36}Ar source appears to have some merit. On the other hand, a more serious investigation must address many other concerns. To what densities can the target be compressed? What is the resultant irradiation strategy and maximum ϕ_n? How thick must the containment vessel be and what effect will it have on ϕ_n? These and other engineering questions are presently unanswered.

Note added in proof. Two comments made recently to me are quite intriguing. William Wilkes suggests that an on-line single-pass extraction system could be built to remove ^{37}Ar from the ^{36}Ar source during irradiation, thereby avoiding the burn-up problem. One would then need only ~1 kg of ^{36}Ar to produce a 1-MCi source. Ray Davis points out that argon can be flushed from various calcium compounds by a helium purge. Thus ^{37}Ar could be milked from a large ^{40}Ca target exposed in some energetic neutron flux. The ^{40}Ca(n,α) cross section at higher neutron energies is known[15] ($\sigma_n\sim59$ mb at 3 MeV and $\gtrsim$200 mb at 5.7–7.5 MeV). A modest cross section could be quite satisfactory because the target material is inexpensive. Each of these schemes has the advantage of producing an extremely compact source that might be of interest in various terrestrial neutrino experiments. For instance, Wilkes's proposal might yield a 100-g 1-MCi source (~10% ^{37}Ar).

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