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ACCELERATOR CALIBRATION OF SOLAR NEUTRINO DETECTORS

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Abstract

We discuss accelerator production of neutrinos in underground laboratories via the $^{12}C(p,n)^{12}N$ reaction. Proton beams within the reach of current accelerator design and economic constraints can produce fluxes up to ten times that attributed to the sun. Intense neutrino fluxes in low-background environments would open up new possibilities for calibrating and developing solar neutrino detectors and for other low-energy neutrino physics.

The 'puzzle' of the missing solar neutrinos has aroused considerable and sustained interest because of its implications for stellar evolution and particle physics[1]. This interest intensified with the discovery of the Mikheyev-Smirnov-Wolfenstein (MSW) mechanism: neutrino mixing characterized by small neutrino masses and mixing angles can alter the flux, spectrum, and flavor of solar neutrinos[2]. There has also been considerable progress on the experimental front. Measurements from the Kamioka II (KII) detector[3], which is sensitive to the high energy portion of the ^8B solar neutrino flux, and the first results from two radiochemical gallium detectors[4], which are primarily sensitive to the low-energy pp neutrinos, have been added to the twenty-year data set from the Homestake Mine ^{37}Cl detector[5], which primarily measures the flux of the ^8B and ^7Be neutrinos. Within the next few years SNO[6] and SuperKamiokande[7] should be taking data. These new direct-counting detectors will be the first to provide high statistics, and will also be able to more clearly characterize the flavor and direction of the astrophysical neutrino flux.

Both the importance and difficulty of direct calibrations of solar neutrino detectors with terrestrial neutrino sources have long been appreciated. The very-low-energy response of radiochemical detectors can, in principal, be tested[8] with radioactive sources such as ^{51}Cr,^{65}Zn, or ^{37}Ar. The reactor physics and safety issues associated with the production, handling, shielding, and transportation of sources of the requisite intensity ($\sim$ 1 MCi) are considerable. For this reason the Homestake detector has never been directly calibrated. Calibration of the GALLEX detector will soon be attempted with a ^{51}Cr source produced from isotopically enriched ^{50}Cr in a French reactor and transported to the Gran Sasso laboratory. Plans exist for a similar calibration of SAGE.

A novel alternative calibration scheme was suggested in 1973 by Marrs *et al.*[9], who explored the feasibility of testing the response of the ^{37}Cl detector to high energy neutrinos by using a small accelerator to produce short-lived ^8B at the detector site. A number of developments have led us to reconsider and extend this idea:

• The sophisticated active detectors now under construction have relatively high thresholds, $\gtrsim 5$ MeV. Accelerators offer the only possibility for producing calibration neutrinos of the requisite energy.

• Underground laboratories now exist that are far more accessible and far better equipped than those of 1973. One can move equipment into such laboratories and meet the power and shielding requirements for accelerator operation.

• While the calibration requirements for radiochemical detectors are largely unchanged, active detectors have more specific signals that are generally less easily mimicked by accelerator byproducts like neutrons. (In radiochemical detectors neutrons can produce energetic protons by the (n,p) reaction, and subsequent (p,n) reactions can produce the daughter isotope.) Furthermore detectors that have directional sensitivity can separate the contributions of solar and calibration neutrinos.

• Most important, Marrs *et al.* focused on the production of ^{8}B neutrinos. We will argue that other β emitters generate very similar neutrino spectra but are far easier to produce. In fact, as the MSW mechanism generally distorts the solar spectrum, the production of a terrestrial neutrino source that exactly mimics the ^{8}B spectrum is no longer a rational requirement. Instead, the calibration goal should be to demonstrate that a detector responds properly to a known neutrino flux similar to that expected from the sun.

Marrs *et al.* considered the production of ^{8}B by the ^{6}Li(^{3}He,n) reaction. If we take as a lower bound for an interesting neutrino flux that measured by the KII collaboration (0.46 of the standard solar model (SSM) flux, or $\sim 2.7 \times 10^6/\mathrm{cm}^2\mathrm{s}$)[3], then the Marrs *et al.* estimates would require a ^{3}He$^+$ current of 110mA at 24 MeV. This assumes that the neutrino flux is measured 8m from the target, which is an effective distance to the center of the Homestake detector vessel in a geometry allowing 5m of shielding against

neutrons produced in the target. Marrs *et al.* concluded that currents considerably less than this value, e.g., 30mA, while not impossible to achieve, would likely be prohibitively expensive to produce.

We now argue that accelerator production of ^{12}N via the ^{12}C(p,n) reaction is a more practical neutrino source than ^{8}B. The advantages of this source over that considered by Marrs *et al.* are:

• The ^{12}N neutrino spectrum is somewhat harder than that of ^{8}B: the β decay endpoints are 16.833 and $\sim$ 15 MeV, respectively. (The final state in the ^{8}B decay is a broad resonance.) Because of the rapid increase of detection efficiency with E_ν, a lower source activity is needed for the same counting rate.

• Protons have lower ionization energy losses than ^{3}He ions. This translates into a greater yield for a given beam current and fewer problems with power dissipation in the target.

• Substantial improvements[10] have recently occurred in the design of high-current, compact accelerators producing protons in the energy range $\sim$ 30 - 50 MeV. The beam energy and current requirements for producing the requisite quantity of ^{12}N can now be satisfied.

On the other hand, there is no disadvantage to using a ^{12}N source rather than ^{8}B. The mean and maximum neutrino energies are so similar that detector responses (electronic or chemical) should not differ appreciably. The beta decay spectra for both sources can be calculated very reliably.

In Fig. 1 we show the normalized neutrino spectra for the β decay of ^{12}N and ^{8}B. The ^{12}N results are calculated from the measured β decay branches[11] to the ground (94.55%), 4.40 MeV (1.90%), 7.65 MeV (2.7%), 10.3 MeV (0.46%), and 12.71 MeV (0.31%) states in ^{12}C. For the branch to the ground state we include first-forbidden corrections, which are almost entirely fixed by the electromagnetic transition rates for the analog 15.11 MeV transition in ^{12}C. These corrections reduce the low-energy tail of the neutrino spectrum by ~.5% and increase the high energy tail by ~ 3%. The 5.45% of the decays that populate excited states in ^{12}C generate less energetic neutrinos with correspondingly smaller detector cross sections. Their contributions to the spectrum of Fig. 1 have been calculated in the allowed approximation. The ^{8}B spectrum is from Bahcall and Holstein[12].

The spectrum of Fig. 1 will be augmented by activities produced by other $p+^{12}C$ reactions. In this regard the situation is more complicated than that for the $^{3}He + ^{6}Li$ reaction considered by Marrs *et al.*, where the only significant activity accompanying ^{8}B production was ^{7}Be (which produces EC neutrinos at 862 and 384 keV). For $p+^{12}C$ at $E_p \lesssim 50$ MeV the additional activities include ^{13}N (β^+ neutrino endpoint of 1.709 MeV), ^{11}C (β^+, 1.709 MeV endpoint, 99.76%; EC, $E_\nu = 1.982$ MeV, 0.24%), ^{10}C (β^+, 1.911 MeV endpoint, 98.5%; 0.889 MeV endpoint, 1.46%), ^{8}B, and ^{7}Be.

For definiteness, we address the low-energy activities in the context of a possible ^{37}Cl detector calibration. The low-energy activities can only excite the transition to the ^{37}Ar ground state, whose strength is fixed by the ^{37}Ar lifetime. We will return to the high energy activities (^{12}N,^{8}B) later. One expects the cross section for $^{12}C(p,\gamma)^{13}N$ to be $\lesssim 1$ mb, so this activity is unimportant. The $^{12}C(p,pn)^{11}C$ cross section has been measured and is large, peaking at ~ 100mb near 45 MeV[13]. The resulting relative $^{11}C/^{12}N$ yields are 40 and 31, respectively, at $E_p = 50$ and 40 MeV. However the cross section for ^{11}C neutrinos to produce ^{37}Ar is small, 4.25×10^{-47} cm^2, so that their net effect on a ^{37}Cl calibration would be ~ 0.1% that of the ^{12}N neutrinos. The $^{12}C(p,x)^{7}Be$ cross section is also known[14], peaking at ~ 20mb at $E_p \sim 40$ MeV. The thick target $^{7}Be/^{12}N$ yields are 6.0 and 3.6 at $E_p = 50$ and 40 MeV, respectively, and the ^{37}Cl ^{7}Be cross section is 2.34×10^{-46} cm^2. Thus, as in the case of the Marrs *et al.* proposal, the net effect of ^{7}Be neutrinos on a ^{37}Cl calibration is $\lesssim 0.1\%$. The cross section for

$^{12}C(p,pnn)^{10}C$, Q = -31.84 MeV, does not appear to have been measured, but with a neutrino cross section on ^{37}Cl of 8.59×10^{-46} cm^2, its contribution to a calibration will be similar to the other cases we have discussed.

In contrast, any significant production of ^{8}B would be important. The relative yields of ^{8}B and ^{12}N activities from proton bombardment of thin C targets have been measured at the Paul Scherrer Institute[15]. The ratio $\sigma(^{8}B)/\sigma(^{12}N)$ is 0.28 and 0.36 at $E_p = 50$ and 70 MeV, respectively. A measurement of the thick-target yield of ^{8}B at energies of interest (e.g., 40 MeV) would be useful. The results of Ref. 15 can be combined with the cross sections given below to estimate that at $E_p = 50$ MeV, the contribution of ^{8}B ν's to the calibration of the ^{37}Cl and KII detectors will increase the counting rates by 12% and 11-13%, respectively. This, of course, is a welcomed result.

We now consider the effects of the high energy activities (^{12}N,^{8}B) on two existing detectors, KII and Homestake. We take the KII resolution and efficiency functions from the parametrizations of Ref. 16. The KII experimenters make software cuts on the apparent energy, ϵ_A, of recorded events to improve the signal/background ratio. Results have been reported for $\epsilon_A^{min} = 9.3$ and 7.5 MeV, and with $\epsilon_A^{max} = 15$ MeV; we have adopted these values in our calibration estimates. The ^{37}Cl detector response is computed from the ^{37}Ca β decay ft-values measured recently by Garcia *et al.*[17].

Folding the normalized ^{8}B neutrino flux with the ^{37}Cl detector response yields $\langle\sigma(^{8}B)\rangle = 1.09 \times 10^{-42}$, while the corresponding value for ^{12}N ν's is $\langle\sigma(^{12}N)\rangle = 2.46 \times 10^{-42}$, a factor of 2.26 larger. This is a result of the harder ^{12}N spectrum and the high effective threshold of the ^{37}Cl detector. (Most of the transition strength is carried by the analog state which lies ~ 5 MeV above the ^{37}Ar ground state.) The corresponding values for the KII detector are $\langle\sigma(^{8}B)\rangle = 2.86(5.52) \times 10^{-45}$ cm^2 and $\langle\sigma(^{12}N)\rangle = 7.35(11.87) \times 10^{-45}$ cm^2 for $\epsilon_A^{min} = 9.3$ (7.5) MeV, so that the cross section ratio is 2.57 (2.15).

Clearly the larger cross section is one advantage of a ^{12}N source over a ^{8}B source. Another advantage derives from the beam requirements. The $^{12}C(p,n)^{12}N$ cross section has been measured from threshold (18.9 MeV) to 50 MeV: it climbs quickly to a maximum of $\sim$ 4mb at $\sim$ 22 MeV then falls smoothly to $\sim$ 1.5 mb at 50 MeV[18]. We folded this cross section with the energy loss rates for protons in carbon to obtain the thick-target yield of ^{12}N as a function of the incident proton energy. The results for 1 mA beams at 40 and 50 MeV are 0.95 and 1.4×10^{12} $^{12}N's/s$, respectively.

We assume, following Marrs *et al.*[9], that a practical geometry, given neutron shielding requirements, would place the target five meters from the side of the detector; 8m is then a reasonable $1/r^2$ distance for calculating an effective flux. [Marrs *et al.* made this estimate for the ^{37}Cl detector; in larger active detectors with position sensitivity the interesting question arises of choosing the fiducial volume to optimize the signal/noise.] At such a distance an interesting ^{12}N neutrino flux is $10^6/cm^2s$. This flux would generate a 1.79 SNU signal in the ^{37}Cl detector, equivalent to 81% of the solar yield[5] of 2.2 $\pm$0.3 SNU (1σ). In the KII detector the corresponding signal is 32% (27%) of the SSM counting rate, given ϵ_A^{min} = 9.3 (7.5) MeV; these rates can be compared to the observed signal of (0.46 $\pm$ 0.05 (stat) $\pm$ 0.06 (sys))SSM[3]. In Fig. 2 we give the beam currents required to produce this flux as a function of the beam energy. Currents of 5.8 and 8.5 mA at 50 and 40 MeV, respectively, are required. (Of course, the detector rates will be $\sim$ 10% larger due to the coproduced ^{8}B neutrinos discussed earlier. We omit this correction here and below.)

What would be necessary to produce a convincing calibration of the Homestake and KII detectors? In the case of Homestake, the 1σ fractional variation in the counting rate, assuming 60 day runs, is 51% of the mean signal of 2.2 SNU[19]. Demanding a 10σ calibration signal of 11 SNU, or about 5 times the mean signal, the expected 1σ variations in a 60-day run would then be 19% of the anticipated 13.2 SNU signal[18].

This result would then require beams of 36 and 52 mA at 50 and 40 MeV, respectively.

Such beams are not excluded by technical constraints. At Los Alamos an effort is underway to build a 200 mA 40 MeV accelerator. The estimated completion date is four or five years from now. The machine, not counting the transport line or beam stop, will be 41m in length. The research, development and construction costs are estimated at \$50-60M[10]. This project was undertaken as a prototype for future, more energetic high-flux machines. Modifications of this prototype to produce somewhat lower currents, 50-100mA, would reduce both construction costs (to $\sim$ \$30M) and the length of the accelerator while still yielding very high ν fluxes; a 75 mA 50 MeV proton beam would produce an event rate in the ^{37}Cl detector ten times greater than that attributed to the sun. [The 200 mA 40 MeV design has two branches, each consisting of an ion source, a radio-frequency quadrupole, and 20 MeV linac, which are funneled together to feed another linac that boosts the beam energy by an additional 20 MeV. For a lower current machine one would eliminate one branch, and the beam-line elements required for the funnel.] The associated beam powers, of course, are very high and will present experimentalists with special problems. However carbon is stable under quite high temperatures and the 2-4MW power can be dissipated over an area $\sim 1m^2$. So the problems, while formidable, are not insurmountable.

In concluding, we would like to place the present discussion in a broader context. Several extraordinary underground detectors are under construction, some with costs $\sim$ \$50M. Experimentalists have considered calibration schemes with above-ground accelerators. In fact, an attempt is underway[20] to measure the response of ^{37}Cl and ^{127}I detectors to LAMPF beamstop neutrinos ($E_\nu^{max} \sim$ 53 MeV), despite the anticipated high background rates. We are suggesting, as an alternative, that the accelerators could be brought to the detectors, at relatively modest incremental costs, thereby allowing experimentalists to test those detectors in the low-background environments where they work best.

The importance of this extends beyond the calibration of existing detectors to the development of new ones. For instance, the radiochemical ^{127}I detector has the attractive features of a large counting rate (about 10 times that of ^{37}Cl) and extremely low background rates[20,21]. But there are substantial cross section uncertainties. In such a case one could perform a calibration with a small-volume prototype detector, given the beams we have discussed. Another possibility is the modification of water Cerenkov detectors by adding various dissolved salts[21] to open up new channels (nuclear γ ray cascades, spallation neutrons) for neutral current interactions: the flavor content of the solar neutrino flux is a crucial issue. As such modifications would alter both the neutrino signals and the optical properties of the detector, the ability to calibrate prototypes would be essential. Finally, one should not rule out the possibility that intense underground neutrino sources might allow one to use existing detectors in low-energy neutrino experiments where background rates would be an inhibiting factor if attempted above ground. Possibilities might include searches for the electron neutrino magnetic moment or for isoscalar weak axial transitions in nuclei.

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Figure Captions

Fig. 1: The normalized spectra of ^{12}N (solid line) and ^{8}B (dashed) neutrinos.

Fig. 2: Beam currents for producing a ^{12}N neutrino flux of $10^6/cm^2s$ 8m from a thick carbon target are given as a function of the incident proton energy.

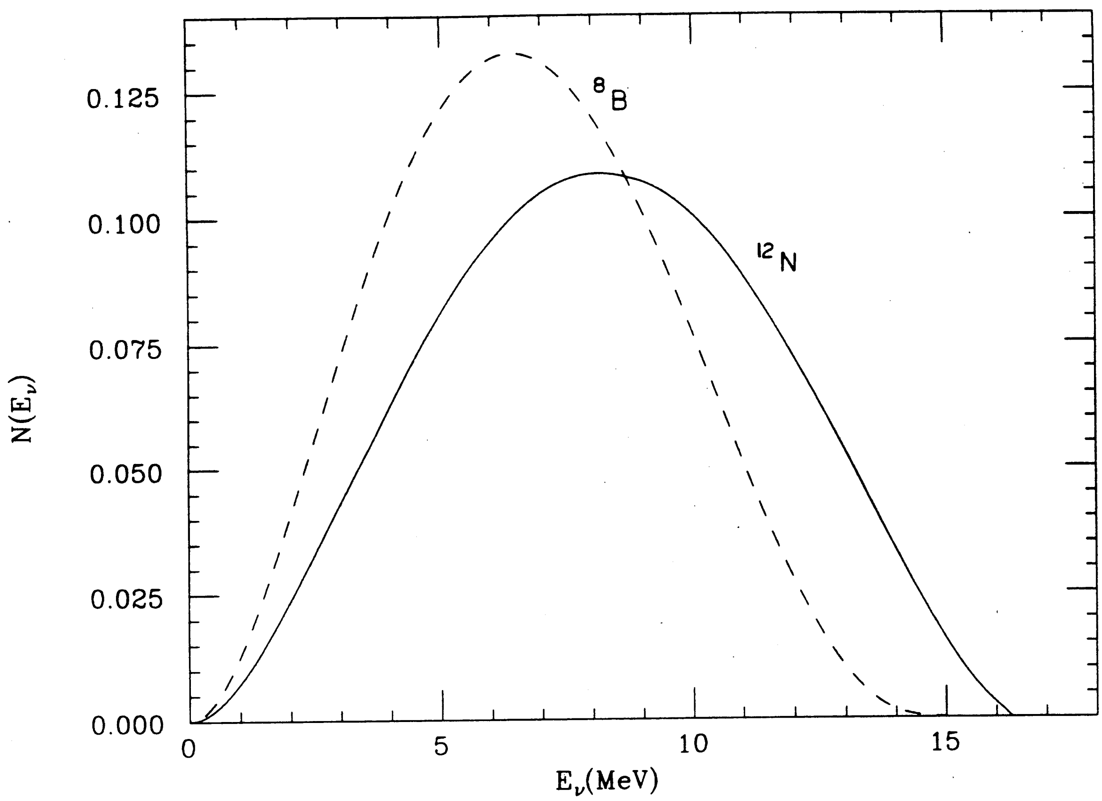

Figure 1

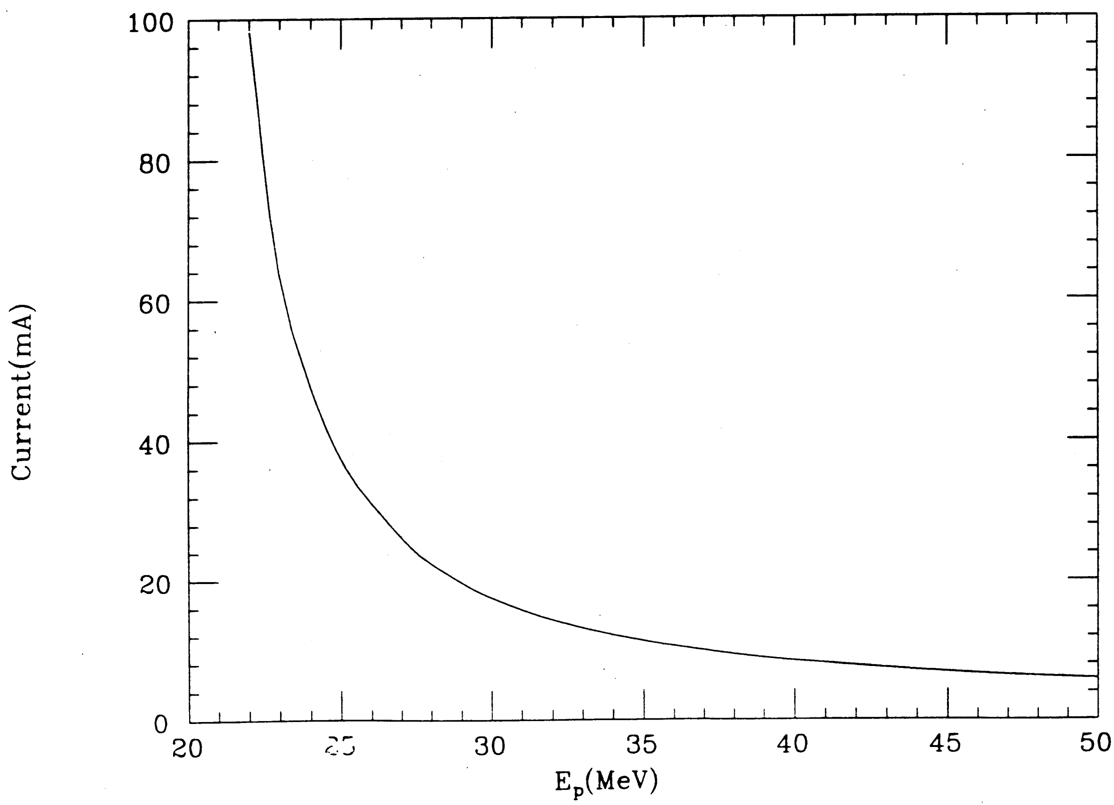

Figure 2