1. The Solar Neutrino Problem – A Long Standing Mystery Solved

The nuclear reactions in the Sun generate electron neutrinos (ν_e), which escape into space. ν interact with matter through weak interactions, they are usually produced during β decays, example $n \rightarrow p + e + \nu_e$. The cross section for ν interacting with matter is very small, $\approx 10^{-44}$ cm^2.

Probability that a ν produced in the center of the Sun interacts with matter before leaving the Sun is $< n_p > R_{\odot}\sigma_{\nu} \ = \ [< \rho > /(\mu m_H)]R_{\odot}\sigma_{\nu} \ \approx 10^{-9}$.

So essentially all ν produced in the Sun stream out from its surface without having interacted with matter within the Sun at all. Only 1 in 10^9 of ν produced in the Sun is intercepted by an inverse β decay before it leaves the Sun.

Table 1. ν Produced Most Frequently in the Sun

Name	Reaction	Energy of ν (MeV)	Davis Detect ?
ppI	$p + p \rightarrow D + e^+ + \nu_e$	0.26	No
ppII	$^7Be + e^- \rightarrow^7 Li + \nu_e$	0.80	No
ppIII	$^8B \rightarrow e^+ + \nu_e +^8 Be^*$	7.20	Yes
CNO	$^{13}N \rightarrow^{13} C + e^+ + \nu_e$	0.72	No
CNO	$^{15}O \rightarrow^{15} N + e^+ + \nu_e$	0.98	Yes
pep	$p + e^- + p \rightarrow D + \nu_e$	1.0	Yes

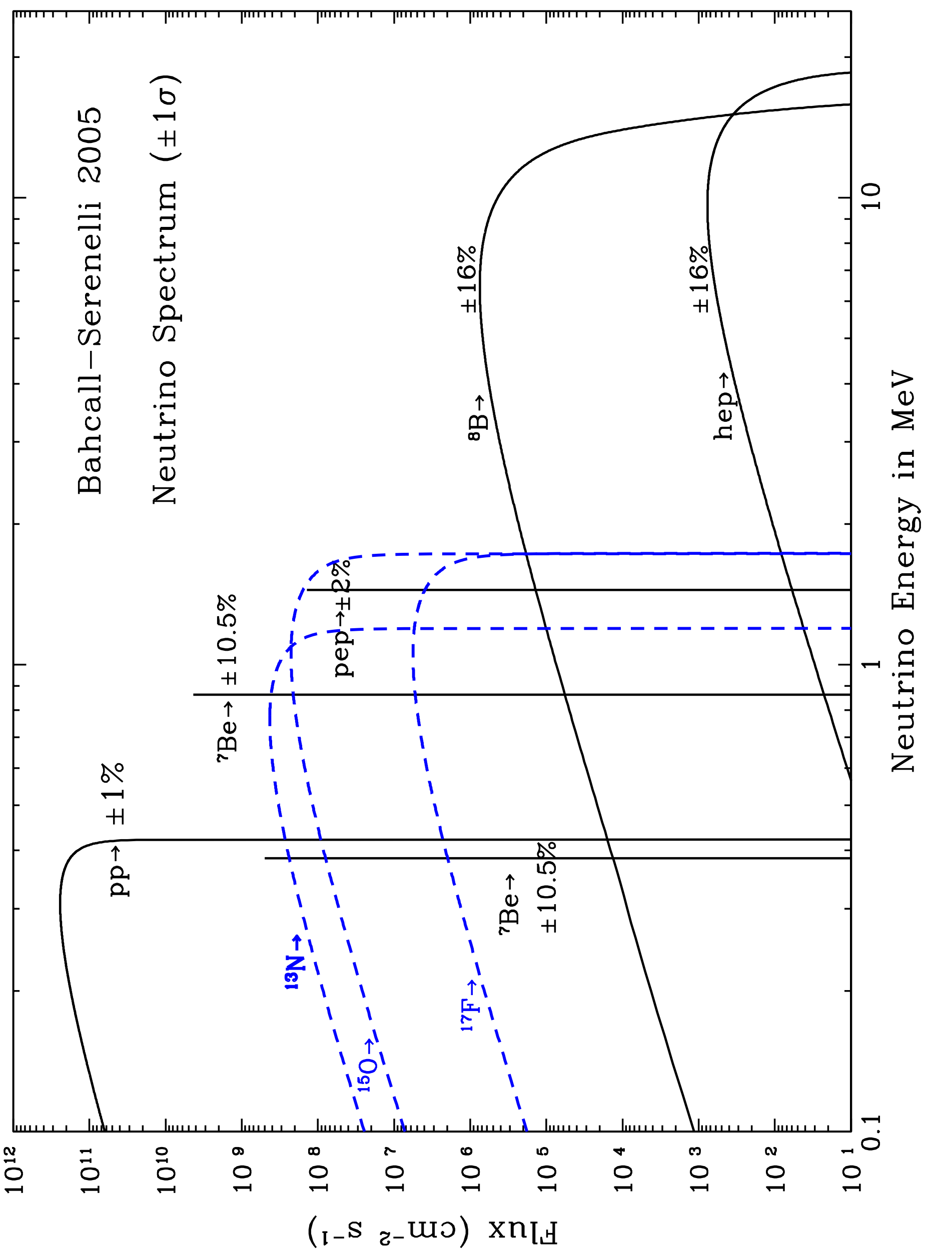

Fig. 1.— The predicted flux of Solar neutrinos at the Earth from various sources assuming the standard Solar model, from John Bahcall.

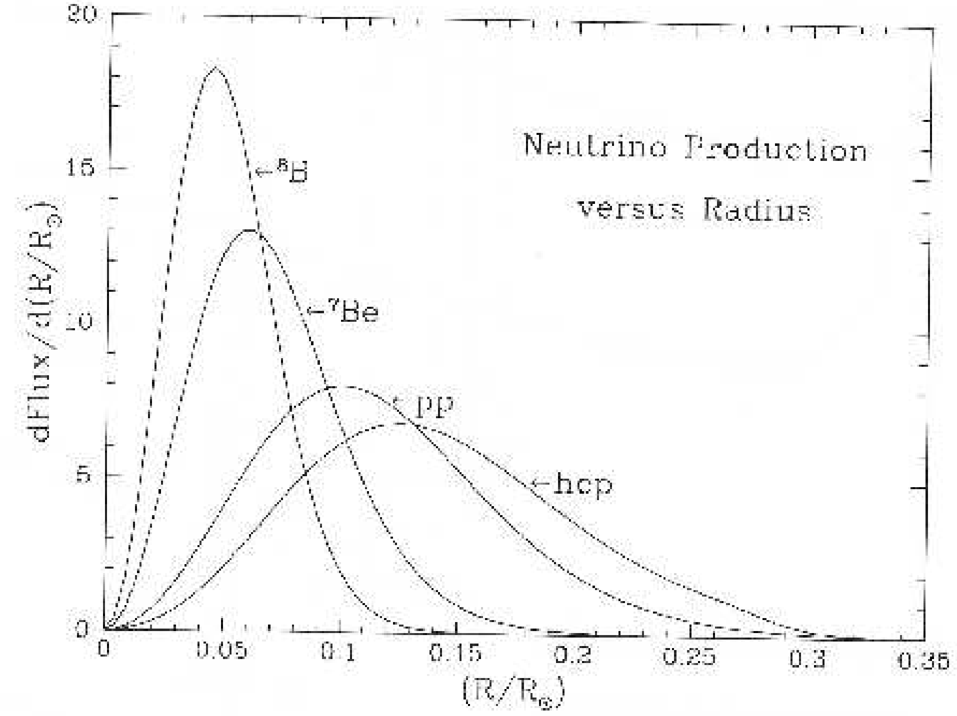

Fig. 2.— The range of Solar radius over which the various reaction (^{8}Be, ^{7}Be, pp, hep) produce ν in the Sun assuming the standard Solar model, from John Bahcall. The X axis is radius in units of the solar radius. The Y axis is $d(Flux)/d(R/R_\odot)$. The individual curves are normalized such that the integral over radius is 1; their heights to not represent the total flux of each type of neutrino.

The Davis Experiment A major long term attempt to detect Solar ν was carried out by Ray Davis (Nobel Prize 2002) in the Homestake Mine, South Dakota, 1500 ft below surface. Uses $^{37}Cl + \nu_3 \rightarrow^{37} Ar^* + e^-$. ^{37}Ar is radioactive and decays with a half life of 35 days. Tank with 4×10^5 liters of C_2Cl_4 (cleaning fluid) inside the mine. Reaction threshold 0.81 MeV, so see ^8B and pep ν. The ^8B ν is produced on a low probability side chain to the main pp chain via the following reactions:

$H + H \rightarrow D + e^+ + \nu_e$ (max E of ν is 0.42 MeV)

$^7Be + e^- \rightarrow^7 Li + \nu_e$ (E = 0.86 or 0.34 MeV)

$^8B \rightarrow e^+ + \nu_e +^8 Be^*$ (E of ν up to 15 MeV)

The pep reaction is $H + P + e^- \rightarrow D + \nu_e$ (E fixed at 1.44 MeV)

The CNO cycle ν from the decay of ^{13}N, ^{15}O, and ^{17}F are not produced in the Sun

The interaction probability of ν is so small that we need a new unit, 1 SNU $\equiv 10^{-36}$ reactions of Cl/sec. The prediction for the Davis experiment: 6 SNU from ^8B decay + 3 SNU from the pep reaction for a total of 9 ± 2.4 SNU total predicted flux.

The observed flux over the period from 1970 to 1988 was 2.1 ± 0.3 SNU.

The Solar ν Problem Many years of work on Davis' ^{37}Cl based ν detector consistently yielded a detection rate roughly 1/3 of that predicted. The discrepancy is many σ and is not due to statistical noise or any known experimental concern.

Assuming their understanding of the experiment, the detection efficiency for ν, and the experimental uncertainties are correct, there are only two potential causes: a) a problem in our understanding of the Solar nuclear reaction rates, or b) a problem in our understanding of the behavior of the ν.

Note that the ^8B ν is coming from an obscure, low probability side reaction in the p-p chain, its probably very sensitive to T, and a small change in the Solar model should fix this problem. John Bahcall investigated in great depth many of the issues of concern under case (a), i.e. is there some way to modify the T we believe to be that at the center of the Sun, a bad value in the nuclear reaction rates, problems in the theory of convection, inhomogeniety of X, Y or Z within the Sun, etc. No such error has been found.

New Experiments New experiments were organized to try to understand this problem. They involve other materials that can detect the lower energy ν coming out of the main pp chain. Gallium has a much lower threshold energy, $^{71}Ga + \nu_e \rightarrow ^{71} Ge^* + e^-$ has an energy threshold of 0.23 MeV and is used by the GALEX experiment running in Gran Sasso, Italy. It has a 30 ton gallium detector deep underground.

This experiment is predicted to detect 70 SNU (pp), 31 SNU (^7Be) and 14 SNU (^8B), for a total of 115 SNU. The actual detected rate is $\approx$75 SNU. Another Ga Russian/US experiment using Ga is SAGE.

Super Kamiokande - this is not a Ga detector, instead big tank of ultra pure water in Japan surrounded by arrays of photomultipliers. The Cherenkov radiation is detected. With this experiment the direction of incoming ν_e can be detected.

All these experiments are underground to cut the background down.

KAMLAND project (Caltech involved in this) is an attempt to measure the ν oscillations directly by placing a detector at variable distances from a set of nuclear reactions used in Japan to generate electricity. This experiment has yielded good evidence for ν oscillations and has confirmed that the pp reactions dominate over the CNO chain in the Sun.

The Sudbury Neutrino Observatory (SNO, www.sno.phy.queensu.ca) in a mine in Canada began opertions in 1999. Using 1000 tons of heavy water (D_2O), it can detect all three flavors of ν, and provided the definitive evidence for ν oscillations.

The Solution: New Physics After much searching, astronomers began to suggest that the answer was acually in our understanding of the physics of ν, if ν have mass (even a very small mass) then they can transform between the various types of ν (ν_e, ν_τ, and ν_μ), so that neutrino oscillations are occuring during the time the ν_e emitted by the Sun propagate from the Sun to the Earth.

The Flux of Solar Neutrinos at the Earth The flux of ν from the Sun at the Earth is easily calculated. We know that $\sim$26 MeV is liberated each time a ^{4}He is produced in the main $p-p$ chain, and 2 ν are produced as well. (We ignore the energy carried off by the ν and we ignore all neutrinos produced in side chains.) Then the number of ^{4}He produced per second is $L_\odot$ /26.2 MeV, which is 4×10^{33} ergs/sec / $26.2 \times 1.6 \times 10^{-6}$ ergs, or 9.5×10^{37} reactions/sec, 2×10^{38} ν produced per second. Dividing by $4\pi(1\ \mathrm{AU})^2$, i.e. $4\pi\ 2.3 \times 10^{26}$ gives a flux of neutrinos at the Earth of 7×10^{10} neutrinos/cm^2/sec at Earth from the main $p-p$ chain.

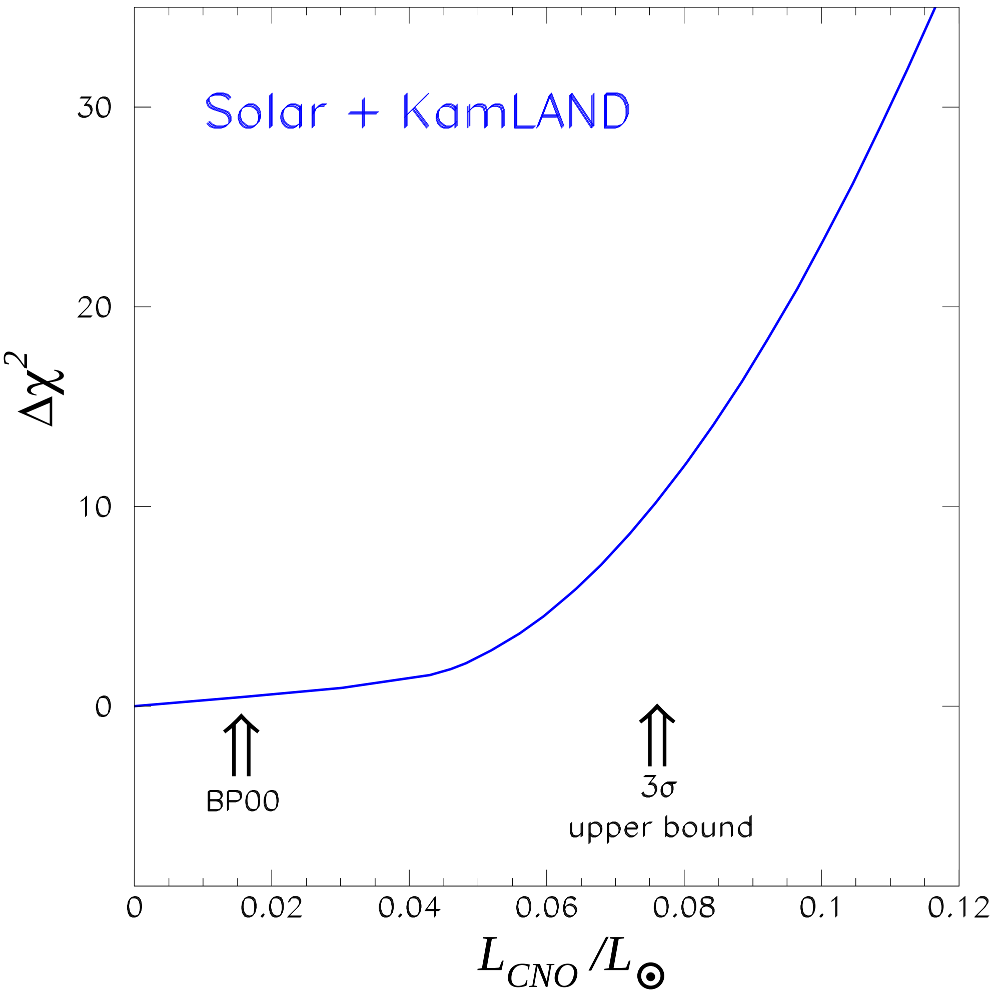

Fig. 3.— The limit set on the fraction of Solar luminosity generated through the CNO reactions assuming the standard Solar model by the Kamland experiment, from John Bahcall.

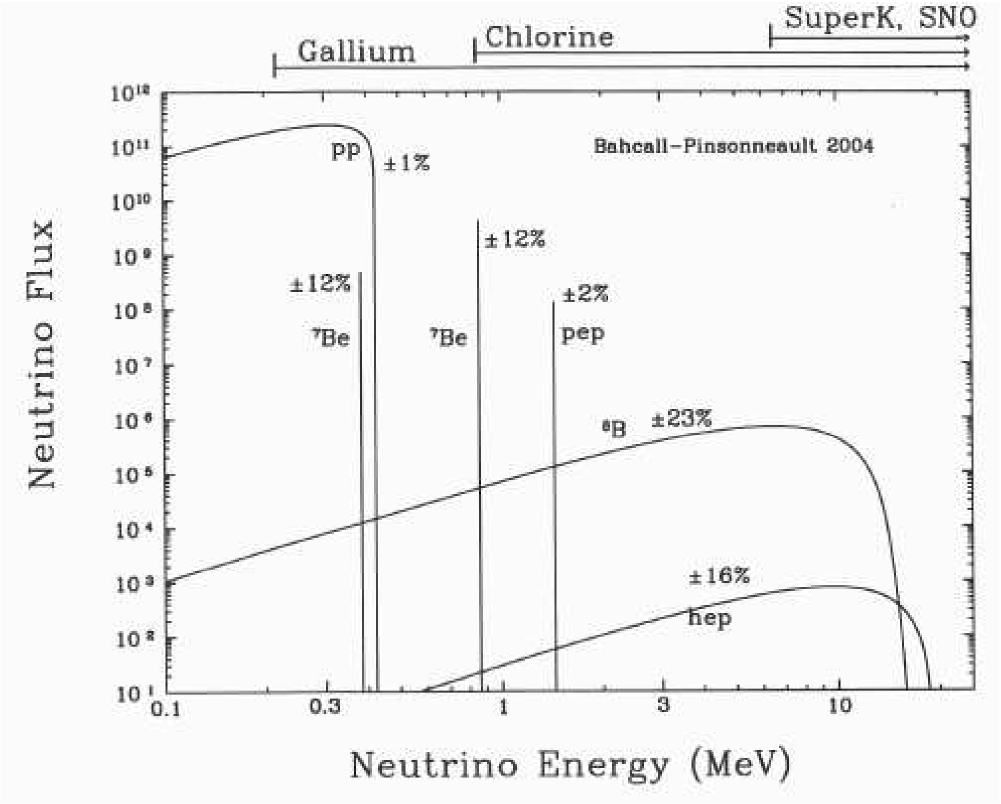

Fig. 4.— The regime of sensitivity of the various neutrino detectors is shown superposed on the predicted flux of Solar neutrinos from various reactions at the Earth assuming the standard Solar model, from John Bahcall.

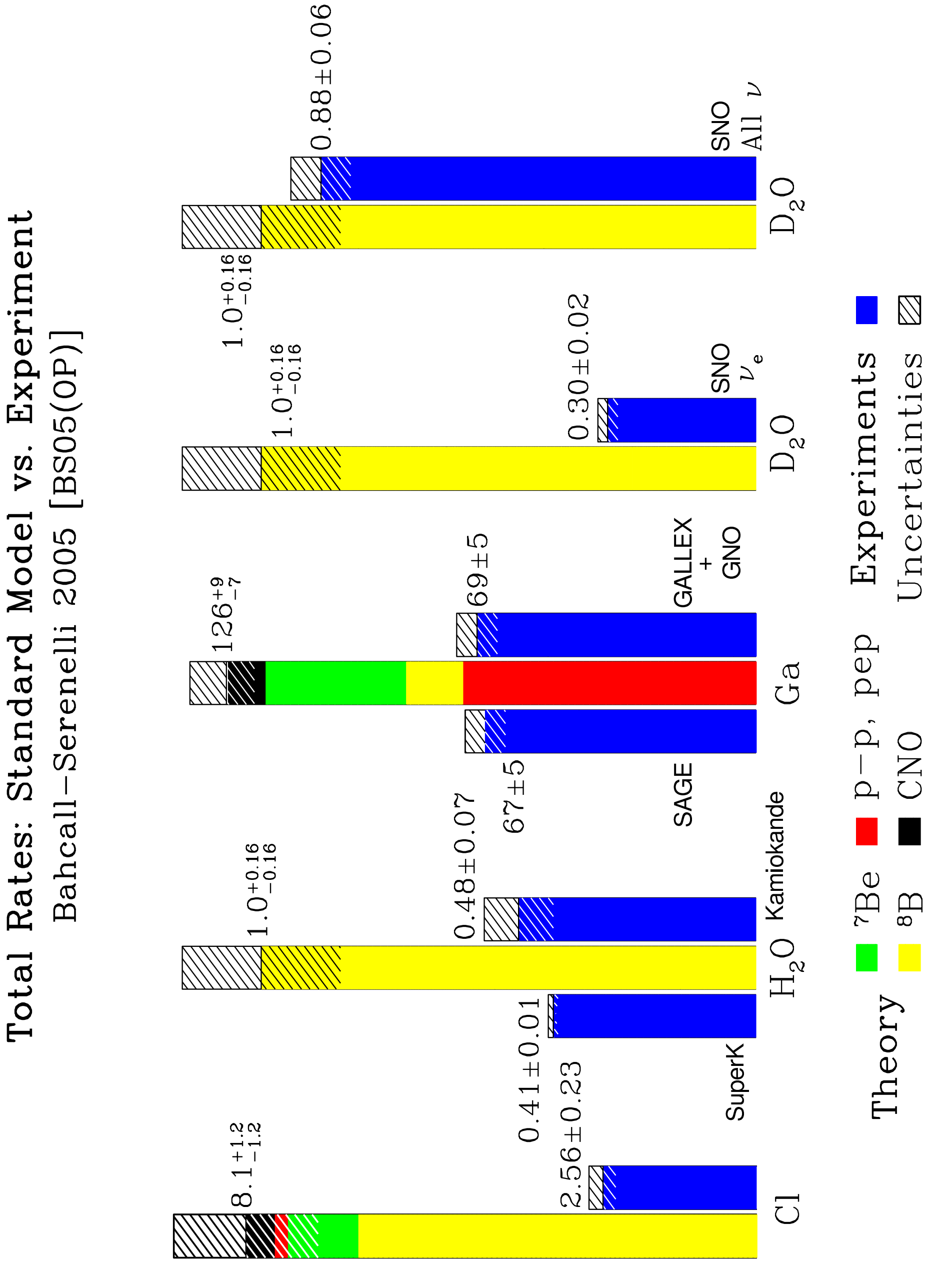

Fig. 5.— The measured versus the predicted flux of Solar neutrinos at the Earth assuming the standard Solar model for various experiments as of 2005, from John Bahcall.

2. Neutrino Production and Cooling

Annihilation Nuetrinos In addition to the ν produced in the p-p chain and such nuclear reactions, ν are produced through pair annihilation between electrons and positrons, $e^+ + e^- \rightarrow 2\gamma$, but one time in 10^{20}, one gets $\nu + \overline{\nu}$ instead.

A photon can diffuse out of a $5M_\odot$ star with $R = 10^{10}$ cm in $\tau_\gamma \approx R^2/(\lambda c)$, where λ is the mean free path for radiation. If λ is from Thompson scattering, $\tau_\gamma \approx 5 \times 10^6$ yr. A larger λ corresponds to a smaller opacity, and τ_γ is smaller.

ν escape without interaction, their energy is lost. $\sigma_\nu \approx (E_\nu/(m_e c^2) 10^{-44}$ cm^2, for $E_\nu = 1$ MeV, $\sigma_\nu \approx 10^{-44}$ cm^2, a factor of 10^{-18} smaller than for photons.

$l_\nu = 1/(n\sigma_\nu) = (\mu m_H)/(\rho\sigma_\nu) \approx 2 \times 10^{20}/\rho$ cm. Thus $l_\nu > R$ for $\rho < 10^{10}$ gm/cm^3.

The energy loss due to ν is thus $Q(\text{pair}) = \; - \int (E_+ + E_-)\sigma v dn_+ dn_- =$ $-4.9 \times 10^{18} T_9^3 e^{-11.89/T9}$ ergs/cm^3/sec. For degenerate electrons this is $Q(\text{pair})$ $= -1.4 \times 10^{15}(1 = (5kt/E_F)T_{10}^4 e^{-E_F/(kT)}$, where $E_F = c\sqrt{(3\pi^2 n_e)^{2/3} + m_e c^2}$.

Photoneutrinos Photon scattering off an electron $\rightarrow \nu + \overline{\nu} + e$ with low probability. Petrosian, Beaudet & Salpeter (1967) worked out the energy loss for such neutrinos (Phys Rev 154, 1445).

Plasma Neutrinos The prohibited reaction starting with a photon, $\gamma \rightarrow e^- + e^+$, is not allowed since both energy and momentum cannot be conserved. However, in very dense material, electromagnetic waves can be quantized into "plasmons", and these behave as if they were a heavy particle which can decay into either $e^- + e^+$ or $\nu_e + \overline{\nu_e}$. This channel is

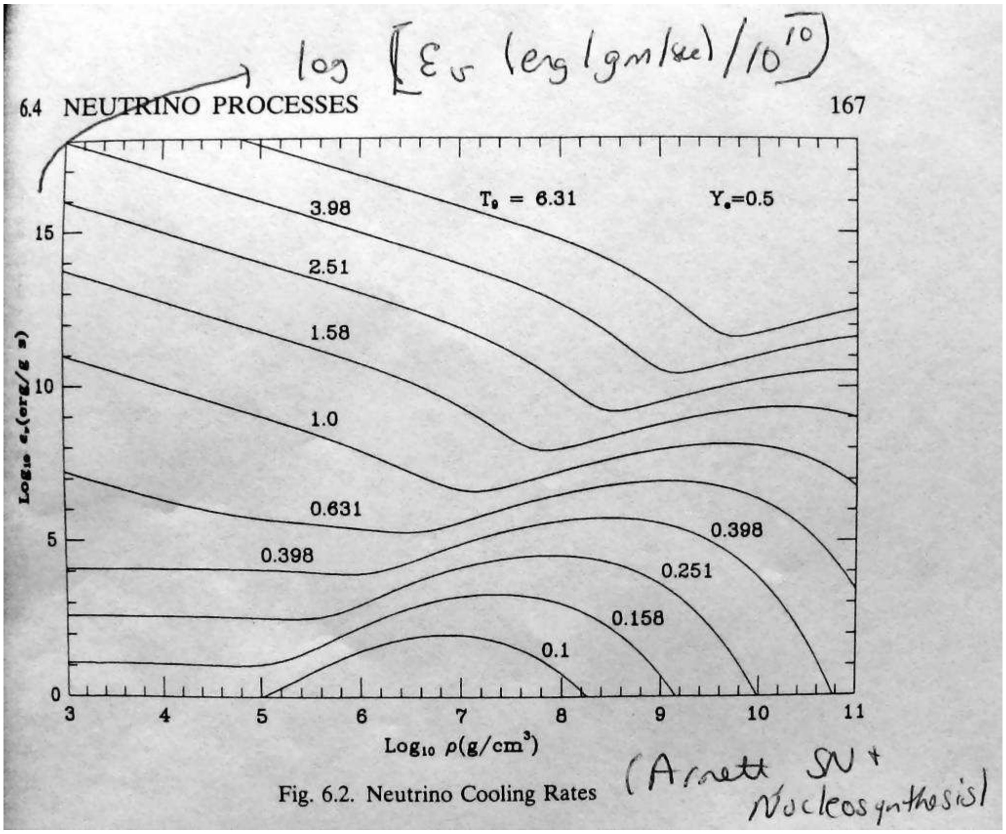

Fig. 6.— Neutrino cooling rates. This is fig. 6.2 of Arnett, *Supernovae and Nucleosynethsis.* The Y axis is logϵ_ν (units ergs/gm/sec) with ϵ in units of 10^{10} ergs/gm/sec. The X axis is logρ with ρ in units of 10^{10} gm/cm^3. The curves are labelled by log(T) with T in units of 10^9 K.

not important under most circumstances.

The URCA Process and Electron Capture At high densities, electron capture (inverse β decay, effectively a proton becomes a neutron, $e^- + p \rightarrow n + \nu$) such that $e^- + (Z,A) \rightarrow (Z-1,A) + \nu$ occurs. This inverse β decay is followed by a β decay, $(Z-1,A) \rightarrow (Z,A) + e^- + \overline{\nu}$. The combination of these two reactions is then effectively $e^- \rightarrow \nu + \overline{\nu} + e^-$. The energy of the two ν is lost, decreasing the thermal energy of the gas. The details depend on the nuclear properties of various elements/isotopes involved and on the abundance of the relevant elements.

ϵ_ν (energy loss/gm/sec from the URCA process) $\approx 1.2 \times 10^{20}$ erg/cm^3/sec $(\rho/\rho_{nuc})^{2/3} T_9^8 (1+F)$, where $F \approx 1$.

The total energy lost through ν is the sum of ϵ_ν for all relevant processes i where i represents the various possibilities for energy loss through ν, including the electron capture reactions (URCA process) on various heavy elements (Z,A). For the total, a rough approximation is:

$\epsilon_\nu \approx 1.1 \times 10^7 T_8^8$ ergs/gm/sec for $T_8 < 6$ and $\rho < 3 \times 10^5$ gm/cm^3.

It is important to recall that only ν_e are produced in the Sun.

Coherent Scattering of Neutrinos $\nu_e + (A,Z) \rightarrow \nu_e + (A,Z)$

$\sigma = \sigma_0 \alpha^2 A^2 E_\nu^2$ cm^2, where α is the weak interaction parameters, ~ 0.2.

Mean free path $l_\nu = (\mu m_H)/(\rho\sigma)$

In a SN, can have E_ν (the mean energy of the neutrinos) be ~ 15 MeV,

$\rho \sim 10^{10}$ gm/cm^3, $A = 56$ (iron), so $l \sim 4 \times 10^6$ cm. There are then several hundred collisions before a ν leaves the star. These are elastic scatterings with no change in energy, but they provide additional time/pathlength for thermalization to occur through the ν.

ν in Supernovae The neutrino burst following core collapse in a SN from a massive star after the Fe core is formed is believed to carry away approximately the binding energy of the neutron star core formed at that time, $\sim 2.5 \times 10^{53}$ ergs. This leaks out on a timescale of $N^2 l/c$, where N is the number of mean free paths to the surface (random walk), so this timescale $\tau \approx R(core)^2/(lc)$. The neutrino luminosity is generated over the entire core, so the total emitted energy in ν is $\sim M(core) E_\nu n_\nu / \rho$.

From theory we can predict the total neutrino energy emitted during core collapse, the timescale for neutrino emission τ, the mean energy E_ν, and the distribution in energy of the emitted neutrinos.

We can compare these predictions to the very small number of ν detected from the explosion of SN 1987A in the LMC. The table below is Table 3 of Arnett et al, 1989, ARAA, 27, 629. SN 1987A is the only extragalactic SN with a detection of ν to date.

Note that only about 20 ν in total were detected, by experiments not intended for this purpose, but rather to measure proton decay, but which happened to be functioning at the time of SN 1987A. For this event, the timescale of ν emission was $\sim$10 sec and the mean energy of the detected events was $\sim$ 15 MeV. The number of detected events, combined with the distance to the LMC and the (low) detector efficiencies is consistent with a total emitted energy in ν (all 6 flavors) of $\sim 2.5 \times 10^{53}$ ergs. The angle of arrival can be measured (with considerable uncertainty) by these detectors and was consistent, at least for the better measurements from Kamionkande, with the direction of the LMC.

Table 2. Measured Properties of Nuetrinos from SN 1987A

Event	Event Time[a] (sec)	Electron Energy (MeV)[c]	Electron Angle[b] (Deg)[c]
Kamiokande II			
1	0.0	20.0±2.9	18±18
2	0.107	13.5±3.2	40±27
3	0.303	7.5±2.0	108±32
4	0.324	9.2±2.7	70±30
5	0.507	12.8±2.9	135±23
6	0.686	6.3±1.7	68±77
7	1.541	35.4±8.0	32±16
8	1.728	21.0±4.2	30±18
9	1.915	19.8±3.2	38±22
10	9.219	8.6±2.7	122±30
11	10.433	13.0±2.6	49±26
12	12.439	8.9±1.9	91±39
IMB			
1	0.0	38±7	80±10
2	0.41	37±7	44±15
3	0.65	28±6	56±20
4	1.14	39±7	65±20
5	1.56	36±9	33±15
6	2.68	36±6	52±10
7	5.01	19±5	42±20
8	5.58	22±5	104±20

[a] The first events were detected on Feb 23, 1987, at about 7:36 UT.