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THE MANY ASPECTS OF NEUTRINO PHYSICS*

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ABSTRACT

In mid-November, over seventy physicists gathered at Fermilab for an informal workshop on *The Many Aspects of Neutrino Physics*, which dovetailed with and also helped lay the groundwork for the succeeding more narrowly focused conference on Long Baseline Neutrino Oscillations. The workshop indeed covered many of the interrelated aspects of neutrino physics: 17 keV neutrinos (experiments, theoretical models, and astrophysical constraints), neutrino properties (double beta decay experiments, neutrino magnetic moments), neutrinos from/as weakly interacting massive particles (WIMPs) in cosmology and astrophysics, atmospheric neutrinos, and solar neutrinos. In the following, I provide a brief and thoroughly biased account of only some of the many interesting developments discussed at the workshop.

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1. The 17 keV Neutrino

In 1985, Simpson[1] reported observation of a distortion of the β decay spectrum of tritium, consistent with the assumption that the electron neutrino is a mixture of two mass eigenstates, $|\nu_e\rangle = \cos\theta|\nu_1\rangle + \sin\theta|\nu_2\rangle$, with the heavy eigenstate $m_{\nu_2} \simeq 17$ keV, the light eigenstate $m_{\nu_1} \lesssim 10$ eV, and a mixing probability $\sin^2\theta \simeq 0.03$. Shortly thereafter, a number of experiments, primarily using ^{35}S, failed to find evidence for the 17 keV neutrino, and the subject lay somewhat dormant, although Hime and Simpson reported new positive evidence in 1989, with a revised mixing probability of about $\sin^2\theta \simeq 0.01$.

Within the last year or so, several groups have reported positive evidence for the 17 keV neutrino in experiments using several different isotopes. Moreover, those groups which earlier found negative results have either completed new experiments, also negative, or are in the process of conducting them. The situation as it stood recently is shown in Table 1. It remains true that, for the most part, the positive results have been found in experiments using solid state detectors, while the null results have been obtained with magnetic spectrometers.[2] A number of issues, such as scattering as a function of source thickness, backscattering from the detector and its effect on efficiency, pileup, shape corrections and distortions, etc., were discussed and clearly deserve further study. New experiments coming on line will be eagerly awaited[3], but it will take a major advance for either side to declare defeat.

It would therefore be useful to have complementary approaches to the problem. An example is the proposed Fermilab neutrino oscillation experiment P-803. In the mass range of interest, $\delta m^2 \simeq m_2^2 \simeq 3\times10^8$ eV^2, neutrino oscillation experiments at Brookhaven preclude a $\nu_e \leftrightarrow \nu_\mu$ mixing angle larger than $\sin^2\theta_{e\mu} \simeq 9\times10^{-4}$, so the heavy mass eigenstate cannot be predominantly ν_μ. (An exception to this statement can arise when one considers simultaneous mixing between all 3 neutrinos–see below.) Combined with accelerator limits on the number of isodoublet lepton families, this leaves only $(\nu_\tau)_L$ as the dominant component of $(\nu_2)_L$. (The 17 keV state cannot be a new isosinglet neutrino, since its required mixing with ν_e would bring it into thermal equilibrium in the early universe, leading to $N_\nu = 4$ neutrino species contributing at the time of primordial nucleosynthesis; this violates the bound from the ^{4}He abundance, as discussed below). The current oscillation bound on $\nu_e \leftrightarrow \nu_\tau$ mixing for large δm^2 is roughly $\sin^2\theta_{e\tau} \lesssim 0.03$ (from BEBC SPS), consistent with the mixing level claimed in the positive beta decay experiments. However, P-803 will be sensitive to $\nu_e \leftrightarrow \nu_\tau$ mixing down to $\sin^2\theta_{e\tau} \simeq 1.3\times10^{-3}$ at the 90 % confidence level, and should clearly see or definitively rule out the 1 % mixing claimed for the 17 keV neutrino. (In addition, we can always wait for the next galactic supernova, with which underground detectors should be able to provide better information on the ν_τ mass.)

By any reckoning, the 17 keV neutrino, while an experimenters' heaven, is a theorists' hell. How does one construct particle physics models for the heavy neutrino $(\nu_h) \simeq (\nu_2)$, a particle as unwanted as the muon? A considerable phenomenological literature has developed in the last year.[4] There are basically two choices: ν_h is either a Majorana or Dirac fermion. If it is Majorana, its contribution to the 'effective' $\nu_e\nu_e$ Majorana mass $\langle m_\nu\rangle_M$ would be $\sin^2\theta_{eh} m_2 \simeq 170$ eV, but double beta decay experiments require this to be less than about 1.6 eV (see section 2). The 17 keV contribution must be cancelled by that of some other heavy neutrino, ν_H, with opposite CP phase and mass $m_{\nu_H} \geq 170$ eV. The ν_H could be the ν_μ if $190 < m_{\nu_\mu}$ (keV) < 270 (the upper bound coming from the experimental upper bound on the ν_μ mass, the lower limit from the $\nu_e \leftrightarrow \nu_\mu$ mixing angle bound); or it could be a heavier singlet neutrino, $\nu_H = \nu_s$, with mass $m_{\nu_s} \lesssim 2.4$ MeV and mixing $\sin^2\theta_{es} \gtrsim 10^{-5} - 10^{-4}$ (the upper bound on m_{ν_s} also comes from $0\nu\beta\beta$ constraints– see section 2 below). In these models, the requisite delicate cancellation of the $0\nu\beta\beta$ rate appears to require some tuning of masses and mixing angles, although it may arise naturally if there is a symmetry that protects $\langle m_\nu \rangle_M$. In addition, if $\nu_H = \nu_\mu$, there is no light neutrino left for MSW mixing to solve the solar neutrino problem, unless one introduces an additional light singlet neutrino for this purpose; on the other hand, if $\nu_H = \nu_s$, one must be wary of bounds from big bang nucleosynthesis on the number of equivalent neutrino species N_ν. The nucleosynthesis bound usually quoted in the recent literature is $N_\nu < 3.3$, which means that any new, light particles must contribute the equivalent of less than 3/10 of a massless fermion species, in equilibrium at a temperature comparable to 1 MeV (and $t \sim 1$ sec, when nucleosynthesis begins), to the energy density of the Universe. If this bound is violated, the primordial helium abundance would be in excess of that inferred from observations of metal-poor HII regions.

It is interesting to see where this bound comes from[5]: briefly, increasing the energy density implies a higher expansion rate at a given temperature, which means the weak interactions that keep neutrons and protons in equilibrium freeze out at a higher temperature; as a result, the residual neutron-to-proton ratio is larger, so there are more neutrons synthesized into ^{4}He; in addition, the higher expansion rate means a smaller fraction of neutrons will have decayed by the time nucleosynthesis begins, leaving more available for ^{4}He production. For the standard cosmology, the primordial ^{4}He mass fraction Y_p from nucleosynthesis is well fit by

$$Y_p = 0.228 + 0.010 \ln \eta_{10} + 0.012(N_\nu - 3) + 0.017(\tau_{1/2} - 10.27)$$

where the baryon-to-photon ratio $\eta = \eta_{10} 10^{-10}$, and $\tau_{1/2}$ is the neutron half-life in minutes. An inferred upper bound on the primordial abundance of $D + {}^3He$ implies $\eta_{10} > 2.8$; coupled with an experimental lower bound on the neutron half-life, $\tau_{1/2} > 10.19$, and an inferred upper bound on the primordial mass fraction of ^{4}He, $Y_p < 0.240$, one finds the constraint $(N_\nu - 3) < 0.3$. How soft is this bound? If the observational upper limit on the primordial deuterium-to-hydrogen ratio is softened from 10 to 15×10^{-5}, one finds the weaker constraint $\eta_{10} > 2$; in addition, allowing a primordial ^{4}He abundance as large as $Y_p \leq 0.243$ (within the range of uncertainty of most extrapolations), the expression above gives $(N_\nu - 3) < 0.8$. Without drastic revision of our understanding of nucleosynthesis or galactic chemical evolution, it would be hard to evade the latter bound; models that violate it (for example, those that introduce additional neutrino families) are therefore in serious trouble. However, some models for the 17 keV neutrino violate the former but may satisfy the latter bound; they should be viewed with cautious skepticism but probably not rejected out of hand.

For example, in the models with a heavy singlet, $\nu_H = \nu_s$, $m_{\nu_s} \lesssim 2.4$ MeV, the $\nu_e - \nu_s$ mixing required to cancel the $0\nu\beta\beta$ rate is sufficient to bring ν_s into equilibrium abundance at the time of nucleosynthesis, leading to $N_\nu = 4$. (In fact, because of its mass, the effect of ν_s on nucleosynthesis is different from just adding an extra massless neutrino species if $m_{\nu_s} \gtrsim 0.5$ MeV.) Therefore, in these models, ν_s must decay with a lifetime substantially less than 1 sec, and must have a mass close to the upper bound of 2.4 MeV. In the most favorable case, it appears that the ν_s decay products contribute $\Delta N_\nu \sim 1/2$ at the time of nucleosynthesis; while uncomfortable, this squeezes by the more conservative nucleosynthesis bound. On the other hand, due to its mixing with ν_e, such a heavy singlet neutrino evidently violates the constraints from SN1987A: compared to a 20 keV sterile Dirac neutrino ν_D (see below), the supernova core energy loss rate due to ν_s is $\sim \sin^2\theta_{es}(m_{\nu_D}/2\langle E_\nu\rangle)^{-2} \gtrsim 10^3$, where I've assumed a SN core temperature of order 40 MeV, so ν_s would rapidly drain energy from the young neutron star and severely shorten the timescale for the detected neutrino burst from SN87A. (Note that, unlike sterile Dirac neutrinos, ν_s will not escape freely from the neutron star: its mean free path $\lambda_{\nu_s} \simeq \lambda_{\nu_e}/\sin^2\theta_{es} \simeq 10\sin^{-2}\theta_{es}$ cm is comparable to the neutron star radius, $R \simeq 10^6$ cm; however, this only diminishes the energy loss rate by a factor $\exp(-R/\lambda_{\nu_s}) \sim 1/3$.)

Let us turn to the second possibility for the 17 keV neutrino: that it is Dirac or pseudo-Dirac. One can think of this as two 17 keV Majorana neutrinos with identical mixing to ν_e, which are either degenerate (Dirac) or nearly so (pseudo-Dirac: $m_{\nu_h 1} - m_{\nu_h 2} \lesssim 160$ eV). If ν_h is Dirac, then its left-handed component is mainly $(\nu_\tau)_L$; its right-handed component may either be an active member of an electroweak doublet, $(\nu_h)_R \simeq (\nu_{\mu_L})^c$, or a sterile, singlet neutrino. The first choice is more economical (no need for singlet neutrinos) and has attracted considerable attention from particle physics model-builders; the key is to build in the approximate conservation of the lepton flavor combination $\tilde{L} = L_e - L_\mu + L_\tau$. Such models get around the $\nu_e \leftrightarrow \nu_\mu$ mixing bound by having maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing, which leads to a cancellation of the $\nu_e \leftrightarrow \nu_\mu$ rate; consistency with the atmospheric neutrino constraints on $\nu_\mu \leftrightarrow \nu_\tau$ mixing (see section 5 below) then indicates a very small pseudo-Dirac mass splitting, $(\Delta m_\nu)_{PD} \lesssim 10^{-7}$ eV. The disadvantage of these models is that there is no other light neutrino to mix with ν_e in the MSW solar neutrino solution, although a very light singlet can be added to accomplish this.

On the other hand, if $(\nu_h)_R$ is sterile, one runs into potential problems with supernova 1987a: wrong-helicity neutrinos are produced by helicity-flip and other weak interactions in the core of a hot ($T \sim 30-70$ MeV), young proto-neutron star. Since their interactions are suppressed by a factor $\sim (m_\nu/E)^2$ compared to proper-helicity neutrinos, the sterile, wrong-helicity neutrinos escape unimpeded from the core, rapidly draining away a large fraction of the star's binding energy; by contrast, ordinary ν's diffuse out from the star on the relatively long timescale of several seconds. The result is that the star would cool much more quickly, reducing the timescale of the $\bar{\nu}_e$ burst seen by the Kamiokande II and IMB detectors below acceptable levels. This clearly leads to an upper bound on m_ν for a Dirac neutrino; the question of the moment is: how does this bound compare to 17 keV? The answer is not yet known, since all the relevant physics (correct axial couplings in nuclear matter, partial neutrino degeneracy, non-spin-flip processes, careful treatment of screening and backreaction) is only now being input into supernova codes[7]. The current betting is that this bound will probably shake out somewhere around 20 keV or so.

If the SN1987A bound does end up below 17 keV, models with new right-handed neutrinos would be forced to have additional $(\nu_h)_R$ interactions which keep them from freely escaping the core of the young neutron star. This is difficult but not impossible to arrange without simultaneously bringing the ν_R into thermal equilibrium at temperatures near nucleosynthesis, thereby violating the bound on N_ν.[8] For example, one can require the otherwise sterile neutrinos to have resonant scatterings via a light scalar ($m_\phi \sim 100$ MeV) in the supernova, while their nonresonant annihilations in the early universe are too weak to keep them in equilibrium.

An alternative possibility is that the sterile neutrinos from the SN core decay before they reach Earth to $\bar{\nu}_e$: because they are massive and travel more slowly than the speed of light, if the decay lifetime is of order 10^4 sec, the $\bar{\nu}_e$ signal in underground detectors could be stretched back out to several seconds, with the later events coming from the sterile ν decay[9]. This would get around the upper bound on the Dirac neutrino mass coming from the SN1987a event timescale described above. While an intriguing concept, this option does not work in practice[10]: from the decay products, one ends up with too many neutrino events from SN87a. Moreover, since the sterile neutrinos escape directly from the hot core rather than the relatively cool neutrinosphere, the decay-induced events would have much higher energies than those observed in KII and IMB, as shown in Fig.1. In fact, this argument can be turned around and used to exclude Dirac neutrinos of mass greater than $\mathcal{O}(1 \text{ keV})$ with lifetime $10^{-9}(m_\nu/\text{keV})\text{sec} \lesssim \tau \lesssim 5 \times 10^7 (m_\nu/\text{keV})\text{sec}$ decaying into ν_e, ν_μ, $\bar{\nu}_e$, or $\bar{\nu}_\mu$.

This bound on the mass and lifetime takes on added importance when placed in the context of other cosmological constraints on the lifetime of massive neutrinos. The most reliable bound comes from requiring that the age of the Universe be greater than 10^{10} yr when the photon temperature reaches 2.74 K (*i.e.*, that the mass density of neutrino decay products does not 'overclose' the Universe, $\Omega_\nu h^2 \leq 1$). For neutrinos (with ordinary weak interactions) lighter than a few MeV, this implies $\tau_\nu < 2.3 \times 10^{13} (10 \text{ keV}/m_\nu)^2$ sec. A more stringent bound comes from requiring the Universe to be matter-dominated long enough for large-scale structure to form (density perturbations essentially do not grow when the Universe is radiation-dominated). Roughly, this amounts to the constraint that the relativistic products of the massive neutrino decay not contribute a present energy density substantially in excess of that in the microwave background. For neutrinos which decay early, the decay products have sufficient time to redshift away to meet this constraint. Assuming a scale-invariant initial spectrum of adiabatic perturbations and cold dark matter (*e.g.*, from inflation), the bound is[11] approximately $\tau_\nu \lesssim 10^8$ sec $(10 \text{ keV}/m_\nu)^2$. If this limit is exceeded, the present structure observed on galactic scales would necessitate excessive microwave anisotropy on large angular scales. (If the scale-invariant spectral assumption is relaxed, presumably this bound could be pushed up slightly.) Interestingly, if this limit is saturated, the cold dark matter model does better at reproducing the observed large-scale structure, as Bond and Efstathiou[11] have recently pointed out: in this case, the Universe undergoes *two* transitions from radiation- to matter-dominated epochs, resulting in more power on large scales.

Taken together with the supernova decay constraint, the cosmological bound suggests a 17 keV Dirac neutrino must have a lifetime less than a few yr, but must decay to something *other* than lighter e or μ neutrinos. The problem is that we have run out of options for what the decay products could be: one seems forced to introduce a light singlet neutrino to save the day once more, again at the risk of violating the primordial nucleosynthesis bound. It is also worth mentioning that these bounds complement that arising from the nonobservation of γ rays from SN87a, $\tau \gtrsim 8.4 \times 10^{14}$ sec $B_\gamma(\mathrm{keV}/m_\nu)$, where B_γ is the decay branching ratio to photons.

In the pseudo-Dirac case with sterile ν_R, J. Cline reported a new calculation showing that if the mass splitting $(\Delta m_\nu)_{PD} \gtrsim 10^{-9}$ eV, the resulting $\nu_L \leftrightarrow \bar{\nu}_R$ oscillations in the early universe would bring the sterile species into thermal equilibrium and violate the nucleosynthesis limit on N_ν (unless these oscillations are suppressed by introducing new ν_R interactions, *e.g.,* via Majorons)[8].

Finally, S. Pakvasa discussed alternative explanations for the 'the 17 keV effect', the most plausible being a 17 keV ν_x which is emitted with a 1 % branching ratio in beta-decay not due to mixing with ν_e but due to a new, slightly weaker than weak, gauge interaction. Related ideas along these lines in supersymmetric models have been considered by Roulet[12].

2. Neutrino Properties: Double Beta Decay

Double-beta decay experiments provide important additional constraints on neutrino masses.[13] The dominant process is the 2ν mode, ${}_ZA \to {}_{Z+2}A + 2e^- + 2\bar{\nu}_e$, which occurs in the standard electroweak model and has now been observed in ^{76}Ge, ^{82}Se, ^{100}Mo, ^{128}Te, and ^{130}Te. Understanding of these reactions forms the template for searches for the rarer 0ν mode, which violates lepton number conservation and therefore requires a massive Majorana neutrino and/or right-handed weak currents. (Henceforward, I will ignore right-handed currents and focus on Majorana masses.) Theoretical calculations of the nuclear matrix elements for the first 3 elements above predict 2ν decay lifetimes in excellent agreement with the observed lifetimes. This gives one confidence that the nuclear physics is sufficiently well understood that lower bounds on the 0ν lifetimes can be used to constrain Majorana neutrino masses. The 0ν rate is proportional to the effective Majorana electron neutrino mass $\langle m_\nu \rangle_M$,

$$\langle m_\nu \rangle_M = \sum_i m_i |U_{ei}|^2 \eta_i^{CP} \ ,$$

where the sum is over light ($m_i \lesssim 10$ MeV) neutrinos that mix with ν_e, $\eta_i^{CP} = \pm 1$ are their CP phases, and U_{ei} is the neutrino mixing matrix. For example, the bound from ^{76}Ge, $\tau_{1/2}^{0\nu} > 1.2 \times 10^{24}$ yr, roughly implies the constraint $\langle m_\nu \rangle_M < 1.6$ eV. This places severe constraints on Majorana models for the 17 keV neutrino, which contributes about 170 eV to this sum: its effect must be cancelled at the 1% level by that of a neutrino with opposite CP phase and appropriately chosen mass and mixing. As noted above, there are two ways this has been done in Majorana models: one invokes a massive (190-270 keV) ν_μ or introduces a heavy (few MeV) singlet neutrino. Recently, Haxton[14] has pointed out a new constraint on models of the latter type: even if $\langle m_\nu \rangle_M = 0$, small, ν-mass-dependent corrections to the intermediate-state propagator generate a nonzero rate for $0\nu\beta\beta$ decay; the resulting rate depends on sums over higher powers of the mass eigenstates, *e.g.,* m_i^3.

The ^{76}Ge constraint limits the mass of the heavy singlet neutrino to less than 2.4 MeV, and experiments with enriched Ge could push the limit down to 1 MeV. As noted above, this creates a potential difficulty with the limit on N_ν, because a sterile neutrino that light would be abundant at the time of big bang nucleosynthesis.

Given the 0ν experimental half-life lower limits from Ge, Se, Mo, and Xe, the recent report by Turkevich, etal.[15] of an unexpectedly short half-life for the decay of ^{238}U to ^{238}Pu is puzzling. This experiment used 8.47 kg of uranyl nitrate, purified in 1956 before most of the atmospheric nuclear explosions that disseminated ^{238}Pu fallout, and kept for 33 years in a plastic bag inside a sealed cardboard container in Chicago! The measured ^{238}U half-life, $(2.0 \pm 0.6) \times 10^{21}$ yr, is well below a recent theoretical estimate[16] based on standard 2ν emission, $\tau_{1/2}^{2\nu} \gtrsim 5.2 \times 10^{22}$ yr, and is apparently consistent with 0ν decay with an effective Majorana electron neutrino mass of $\langle m_\nu \rangle_M = 11.4^{+2.2}_{-1.4}$ eV. However, this clearly violates the upper bounds on $\langle m_\nu \rangle_M$ from ^{76}Ge and ^{136}Xe.

Counter experiments can directly probe the electron spectrum in $\beta\beta$ decay, and results have been obtained for ^{76}Ge, ^{82}Se, ^{100}Mo, and ^{150}Nd. The 2ν decay has a broad spectrum, with a characteristic peak at about 1/3 of the transition energy, Q. The 0ν spectrum is a monoenergetic spike at Q; intermediate between these is the case of 0ν decay with emission of a massless Goldstone boson (*e.g.*, the Majoron), which has a broad spectrum peaked near $(3/4)Q$. The spectra for ^{76}Ge and ^{100}Mo are broadly consistent with 2ν decay, but appear to have small (yet statistically significant) bumps at about the energy expected for 0ν decay with Majoron emission[17]. It will be interesting to see what happens to these bumps as more data is accumulated.

3. Neutrino Properties: Magnetic Moments

An area of active investigation by particle theorists in recent years is the possibility of a large magnetic moment for the electron neutrino.[18] The motivation for this work was the suggestion by Voloshin, Vysotskii, and Okun[19] that the purported correlation of the ^{37}Cl solar neutrino signal and the 11-yr solar sunspot cycle could be explained if ν_e's undergo spin-flip to sterile neutrinos as they pass through the magnetic field of the sun's convective zone during periods of high solar magnetic activity. This requires an intense field with large coverage in the convective zone, $B \sim 10^3 - 10^4$ Gauss, and a large neutrino magnetic moment, $\mu_\nu \sim 10^{-11} - 10^{-10}\mu_B$, where $\mu_B = e/2m_e$ is the Bohr magneton.

There are now several theoretical models for generating such large magnetic moments, but the astrophysical constraints on these models are daunting. For a Dirac-type magnetic moment, which arises through an effective Lagrangian term $\bar{\nu}_{eL}\sigma_{\mu\nu}\nu_{eR}F^{\mu\nu}$, the most stringent constraint comes from SN1987a: helicity flips in the supernova core would rapidly cool the nascent neutron star[20], reducing the timescale of the KII and IMB signals; this leads to the approximate bound $\mu_\nu \lesssim 10^{-12}\mu_B$. Thus the solar spin-flip solution must realistically be based on a transition magnetic moment of the form $\nu_{eL}^T C^{-1}\sigma_{\mu\nu}\nu_{\mu L}F^{\mu\nu}$, which violates lepton number. However, there is another astrophysical constraint, nearly as stringent as that from SN1987a, which applies to both Dirac and transition moments: an anomalous neutrino magnetic moment implies a large plasmon decay rate, $\gamma_{pl} \rightarrow \bar{\nu}_i\nu_j$;

in helium-burning stars, the energy loss through this process delays the helium flash, and thus increases the core mass when helium ignites. The latter quantity can be related to the observable properties of horizontal branch and red giant stars[21], with the result that one obtains the bound $\mu_\nu < 3 \times 10^{-12} \mu_B$. Given this constraint, one would require a magnetic field of at least $B \gtrsim 5 \times 10^4$ G with a coherence length comparable to the extent of the convection zone ($L \sim 2 \times 10^{10}$ cm) in order to achieve a significant spin-flip probability (the spin-flip probability is proportional to μBL). The difficulty with this idea is that strong magnetic fields in the convective zone are unstable to magnetic buoyancy[22] and would escape to the solar surface. Even in the lower convective zone, it is estimated[22] that a field of strength larger than about 300 G would escape on a timescale short compared to the 11-year amplification time of the solar dynamo, so it is difficult to understand how fields 170 times stronger than this could be produced. (It is true that significantly stronger magnetic fields could be anchored in the radiative core of the sun, but they would most likely not play a role in generating a time-dependent neutrino signal. In addition, while intense fields of $\mathcal{O}$(kG) are observed at the solar surface, they are very localized configurations; the limit above applies to a field with a large coherence length.)

4. Neutrinos from/as WIMPS

The observed flat rotation curves of galaxies and the application of the virial theorem to clusters of galaxies have revealed the presence of large amounts of dark matter, constituting perhaps 90% of the total mass in these systems. Several lines of argument suggest that much of the dark matter is not baryonic, and the conventional assumption is that it is composed of weakly interacting massive particles (WIMPs). For the last 10 years or so, the preferred form of non-baryonic dark matter among cosmologists has been 'cold' dark matter, particles which are always non-relativistic on astrophysically interesting scales. Currently, the best-motivated cold dark matter candidates are supersymmetric neutralinos and axions, and active experimental searches to detect them are underway. In addition to direct searches using ultra-sensitive low-temperature detectors, neutralinos might be found indirectly via the energetic neutrinos they produce when they annihilate in the sun or Earth (in addition to other annihilation signatures from the galactic halo)[23]. So far, using bounds on neutrino-induced muon events in underground detectors such as KII, IMB, and Frejus, this has been used to place significant constraints on the parameter space of supersymmetry models. Further development will require ingenuity in distinguishing the signal from the background of atmospheric neutrinos (see section 5); future progress along these lines using the MACRO and AMANDA detectors should be watched for.

The other alternative for non-baryonic dark matter is 'hot' dark matter (HDM), and the paradigmatic HDM candidate is a light ~ 30 eV neutrino. (Given the tritium beta-decay limit $m_{\nu_e} < 9$ eV, this leaves ν_μ ($m_{\nu_\mu} < 270$ keV) and ν_τ ($m_{\nu_\tau} < 35$ MeV) as possibilities.) Although HDM has been out of fashion because it does a poorer job at reproducing large-scale structure, it has the oft-stated advantage that neutrinos are known to exist. In addition, HDM may fare somewhat better in scenarios where structure arises from primordial seeds, such as cosmic strings[24]. Recently it has also been suggested that a 30 eV dark matter neutrino which decays radiatively, $\nu_{dark} \rightarrow \nu_{light} + \gamma$, with a lifetime $\tau \sim 10^{24}$ sec could re-ionize the intergalactic medium (IGM)[25]. This could explain the absence of intergalactic neutral hydrogen absorption lines in the spectra of high-redshift quasars (alternatively, one could appeal to an astrophysical source, such as an early generation of active galaxies or massive stars, but no extremely convincing source model has been found yet which adequately re-ionizes the IGM). However, unless evidence for the requisite neutrino mass is forthcoming, HDM will probably remain a minority proposition. Alternatively, one might radically drop the assumption that the density fluctuations responsible for large-scale structure formed in the early universe, and appeal instead to a late-time (perhaps even post-recombination) phase transition to produce structure[26].

5. Atmospheric Neutrinos

Cosmic ray nucleons hitting Earth's atmosphere produced a cascade of mesons which ultimately decay to $e^{\pm}$, ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$. The resulting atmospheric neutrino flux has been observed in underground nucleon decay experiments; in particular, Kamiokande and IMB have accumulated 4.9 and 7.7 kiloton-yr of data, and their results are in good agreement[27]. Over the energy range 0.1 – 2 GeV, the expected flux ratio of muon to electron neutrinos is $F = (\nu_\mu + \bar{\nu}_\mu)/(\nu_e + \bar{\nu}_e) \simeq 2$. Several different Monte Carlo calculations of this ratio have been performed, and the results for F are in agreement to within less than 5% over this energy range. However, defining the ratio $R = F_{data}/F_{expected}$, the experimental results are $R \simeq 0.6$ for Kamiokande and $R \simeq 0.67$ for IMB. The difference between the two experiments can be accounted for by the fact that IMB has a higher threshold for ν_μ combined with the difference in geomagnetic cutoff of the cosmic ray flux at the two locations. The question is whether these results reflect a significant depletion of ν_μ's, which would suggest $\nu_\mu \leftrightarrow \nu_\tau$ oscillations, or an enhancement of ν_e's (with a smaller depletion of ν_μ), which suggests $\nu_\mu \leftrightarrow \nu_e$ oscillations. To decide among these possibilities, one needs predictions for the absolute fluxes (in addition to the flux ratio F); here, however, the calculations differ significantly: the flux results of Barr, Gaisser, and Stanev are 10 – 20 % higher than those of Honda, etal. and Lee and Koh[28]. Thus, the results of Gaisser, etal. suggest $\nu_\mu - \nu_\tau$ mixing, while the latter suggest $\nu_\mu - \nu_e$ mixing. In either case, the required mixing parameters are $\Delta m^2 \simeq 10^{-2} - 10^{-3}$ eV^2, and $\sin^2 2\theta \gtrsim 0.5$. To probe the oscillation scenario for the atmospheric neutrino results and to decide between these two possibilities will require the long baseline neutrino oscillation experiments proposed using the Fermilab beam.[29]

6. Solar Neutrinos

The subject of solar neutrinos was reviewed by J. Bahcall at this meeting, so I will just briefly summarize the recent results. For the Cl and Ga experiments, the most recent standard solar model calculation of Bahcall and Pinsonneault (1992, to be published) gives 7.4 ± 2.8 SNU and 128^{+19}_{-16} SNU, only slightly lower than previous results[30]. The mean result from the ^{37}Cl Homestake experiment is 2.1 ± 0.3 SNU (1σ error), while the Soviet American (SAGE) collaboration, running a ^{71}Ga-^{71}Ge radiochemical experiment with 30 tons of gallium at Baksan, reports[31] a capture rate of $20^{+15}_{-20} \pm 32$ SNU, with a

90% C.L. upper limit of 79 SNU. The Gallex experiment, a similar experiment at the Gran Sasso tunnel in Italy, has been running since May 1991; as of late 1991, 9 runs of 21 days exposure time each had been done, and each run is followed by more than 6 months of counting[32]. The collaboration expects to have publishable results by spring of 1992.

In the new Bahcall model, the ^{8}B flux is reduced by a factor $\simeq 0.9$, so the Kamiokande II results (based on 1040 days of data) give a value that is $0.51 \pm 0.06 \pm 0.07$ times the standard solar model (revised upward from the old value of 0.46). The most elegant way to simultaneously account for the ^{37}Cl, SAGE, and KII results is via non-adiabatic $\nu_e \leftrightarrow \nu_x$ MSW mixing in matter; this requires $\Delta m^2_{\nu_e \nu_x} \sim 10^{-7} - 10^{-5}$ eV^2 and $\sin^2 2\theta_{ex} \gtrsim 10^{-3}$.

In 1990, the Kamiokande detector was upgraded to Kamiokande III with new electronics, new photomultiplier tubes with reflectors for enhanced light capture, and water purification. Kajita reported on 99 days of new KIII data (Jan.-June '91), with the preliminary result $0.73^{+0.20}_{-0.17} \pm 0.10$ for the ^{8}B flux compared to the new standard model of Bahcall. Kamiokande still sees no evidence for time variation in the solar neutrino flux. With only a tenth of the running time, the new KIII results are statistically less significant than the KII results (and consistent with them), yet it will be interesting to see if the suggested trend of a higher ^{8}B flux continues when more data is accumulated. (In particular, if the ^{37}Cl results are explained by MSW mixing, the predicted fractional Kamioka rate should be less than 0.6, independent of mixing parameters.)

7. Conclusion

The neutrino sector currently provides the only tantalizing hints of physics beyond the standard electroweak model, but at this stage we are faced perhaps with an embarassment of riches. For, taken all together, these hints appear to be contradictory: the 17 keV neutrino together with accelerator limits on $\nu_e - \nu_\mu$ mixing implies a heavy ν_τ; unless ν_τ and ν_μ are nearly degenerate, this would mean the atmospheric neutrino results are due to mixing of two very light neutrinos, $\nu_e \leftrightarrow \nu_\mu$, with $\Delta m^2 \simeq 10^{-2} - 10^{-3}$ eV^2 and large $\nu_e - \nu_\mu$ mixing angle. But this is outside the range of parameters for the MSW solution of the solar neutrino problem ($\Delta m^2 \sim 10^{-7} - 10^{-5}$ eV^2 and $\sin^2 2\theta \gtrsim 10^{-3}$). Alternatively, if ν_τ and ν_μ *are* nearly degenerate, their mixing could account for the atmospheric neutrino data, but that leaves nothing light for ν_e to mix with in the MSW solution. With 3 neutrinos, you can't have it all. One can invoke mixing with a fourth, sterile neutrino, for either the atmospheric or solar neutrino problems, but it requires introducing a light electroweak singlet only for this purpose. Thus, we are in a quandary; this is a sure promise that both experimentalists and theorists have challenging problems ahead of them.

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REFERENCES

[1] J. J. Simpson *Phys. Rev. Lett.* **54**, (1985).

[2] S. Freedman, A. Hime, F. Calaprice, and W. Hong presented overviews of the experimental results and issues at this meeting.

[3] J. Mortara and W. Stoeffl discussed magnetic spectrometer experiments in progress. In addition, Stoeffl reported a new upper bound of 9 eV on the electron neutrino mass (95% C.L.) from the Livermore experiment.

[4] G. Gelmini, R. Mohapatra, J. Cline, and S. Pakvasa discussed model-building issues and constraints for the 17 keV neutrino. See G. Gelmini, S. Nussinov, and R. Peccei, UCLA preprint (1991); D. Caldwell and P. Langacker, ITP preprint (1991); J. Cline and T. Walker, Ohio State preprint (1991).

[5] G. Steigman discussed nucleosynthesis limits on new particles. See K. Olive, D. Schramm, G. Steigman, and T. Walker, *Phys. Lett.* **236B**, 454 (1990).

[6] D. Seckel, J. Pantaleone, and R. Gandhi discussed aspects of the supernova bound on sterile massive neutrinos.

[7] G. Fuller, R. Mayle, , D. Schramm, M. Turner, and J. Wilson in preparation. For earlier treatments, see G. Raffelt and D. Seckel, *Phys. Rev. Lett.* **60**, 1793 (1988). R. Gandhi and A. Burrows, *Phys. Lett.* **246B**, 149 (1990) and references therein.

[8] J. Cline and R. Mohapatra discussed models which simultaneously evade these bounds.

[9] J. J. Simpson, *Phys. Lett.* **B**, 1991, in press. J. Cline, preprint.

[10] S. Dodelson discussed limits on decaying neutrinos from SN1987a. See S. Dodelson, J. Frieman, and M. Turner, 1992 Fermilab preprint.

[11] G. Steigman and M.S. Turner, *Nucl. Phys.* **B253**, 375 (1985). J. R. Bond and G. Efstathiou, 1991 preprint. M. Turner discussed structure formation and the 17 keV neutrino.

[12] E. Roulet, private communication.

[13] P. Vogel and M. Moe reviewed double-beta decay theory and experiment.

[14] W. Haxton, *Phys. Rev. Lett.* **67**, 2431 (1991).

[15] A. L. Turkevich, T. E. Economou, and G. A. Cowan, *Phys. Rev. Lett.* **67**, 3211 (1991).

[16] A. Staudt, K. Muto, and H. V. Klapdor-Kleingrothaus, *Europhys. Lett.* **13**, 31 (1990).

[17] The ^{100}Mo results were obtained in the UC Irvine Time Projection Chamber Experiment of M. Moe, M. Nelson, M. Vient, and S. Elliott. The ^{76}Ge results were obtained by F. T. Avignone, etal., *Phys. Lett.* **256B**, 559 (1991).

[18] Models for and implications of neutrino magnetic moments were discussed by D.

Chang, P. Pal, R. Mohapatra, and P. Mohapatra. D. Kennedy discussed implications of the see-saw mechanism.

[19] M. Voloshin, M. Vysotskii, and L. Okun, *Sov. JETP* **64**, 446 (1986). The original idea dates back to E. Cisneros, *Astro. Space Sci.* **10**, 87 (1971).

[20] I. Goldman, Y. Aharonov, G. Alexander, and S. Nussinov, *Phys. Rev. Lett.* **60**, 1789 (1988). J. Lattimer and J. Cooperstein, *Phys. Rev. Lett.* **61**, 23 (1988). R. Barbieri and R. Mohapatra, *Phys. Rev. Lett.* **61**, 27 (1988).

[21] G. Raffelt, *Phys. Reports* **198**, 1 (1991).

[22] E. Parker, *Cosmical Magnetic Fields*, (Oxford University Press, Oxford, 1979).

[23] M. Kamionkowski and E. Roulet discussed limits on supersymmetric particles from annihilation-produced neutrinos.

[24] A. Albrecht and G. Steigman discussed structure formation models with cosmic strings and seeds.

[25] J. Jubas and R. Splinter discussed aspects of this idea.

[26] Recent work on late-time phase transitions was reviewed by R. Watkins. For a recent discussion of models and scenarios, see J. Frieman, C. Hill, and R. Watkins, Fermilab preprint (1991).

[27] The IMB and KII results were reported by S. Dye and T. Kajita. Flux calculations were discussed by T. Gaisser, and S. Pakvasa discussed the implications for neutrino mixing.

[28] G. Barr, T. Gaisser, and T. Stanev, *Phys. Rev.* **D39**, 3532 (1989); Honda, etal. *Phys. Lett.* **24B**, 193 (1990); Lee and Koh, *N.C.* **B105**, 883 (1990).

[29] The complementary idea of probing atmospheric neutrino oscillations with a surface neutrino telescope at the South Pole (AMANDA) was discussed by M. Doncheski.

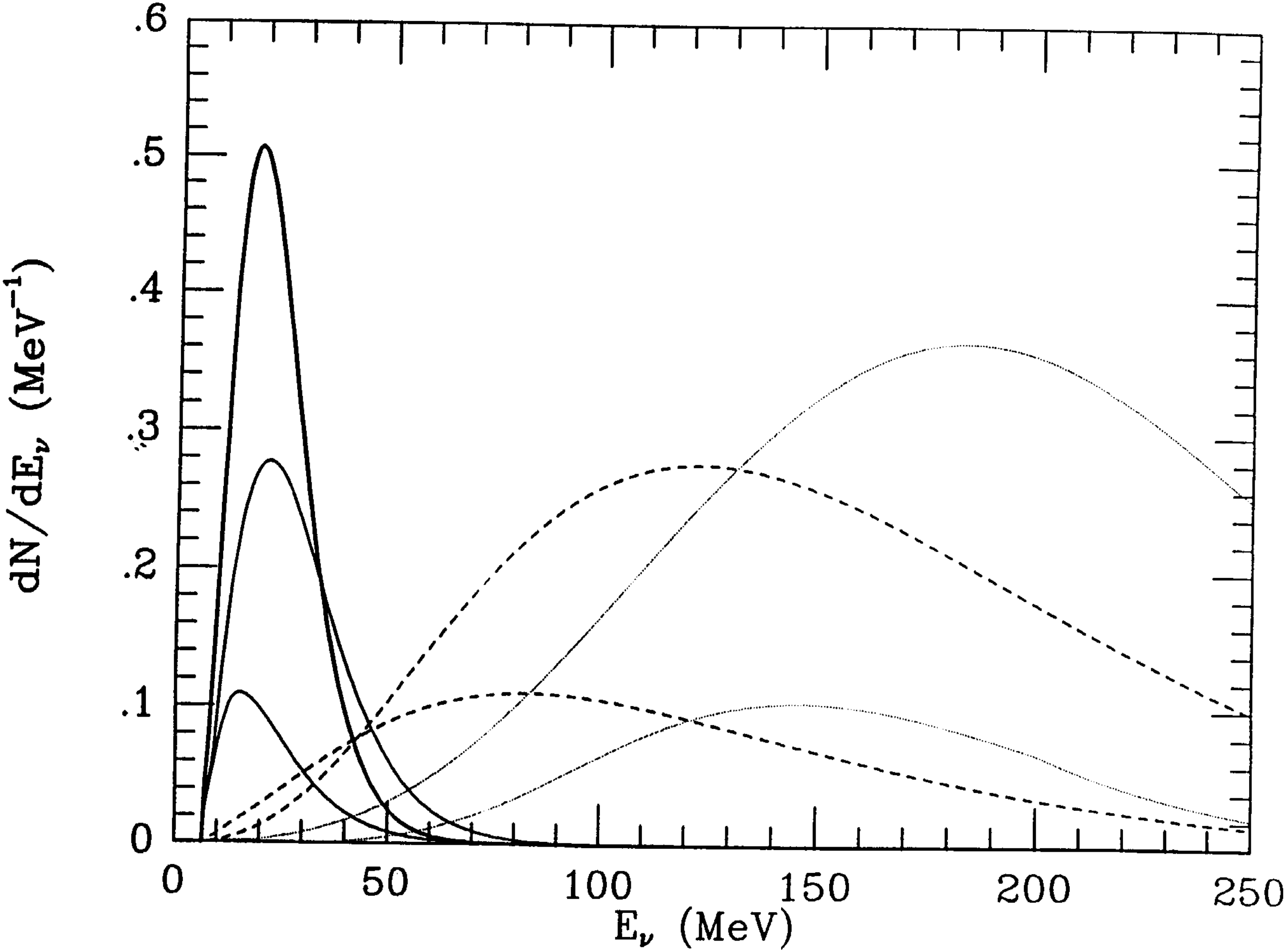
[30] The new ingredients are improved estimates for nuclear cross-sections, opacities, iron abundance, and a more detailed treatment of helium diffusion.

[31] A. Abazov, etal., *Phys. Rev. Lett.* **67**, 3332 (1991). (With the breakup of the Soviet Union, perhaps the experiment should be renamed RAGE.)

[32] K. Lande reported on the Homestake and SAGE results, A. Baltz reported on the progress of Gallex, and Kajita discussed the Kamioka observations. In addition, H. Robertson gave a progress report on the Sudbury Neutrino Observatory, and R. Lanou discussed progress on superfluid helium detectors for solar neutrinos.

Figure Caption

Figure 1: For the KII detector, the energy distribution of SN1987A events produced by $\bar{\nu}_e$'s emitted from the neutrinosphere (solid, top) and by $\bar{\nu}_e$'s produced by the decays of neutrinos emitted from neutrinosphere, nonhelicity-flip decay (solid, middle) and helicity-flip decay (solid, middle); by decaying nondegenerate neutrinos emitted from the core, nonhelicity-flip $\bar{\nu}_e\, p$ events (broken, top) and helicity-flip $\bar{\nu}_e p$ events (broken, bottom); and by decaying degenerate neutrinos emitted from the core, $\bar{\nu}_e\, p$ events (dotted, top) and $\nu_e\, {}^{16}\mathrm{O}$ events (dotted, bottom). The neutrinosphere temperature for the decaying neutrino is taken to be 7 MeV; the core temperature to be 40 MeV; and neutrino chemical potential $\mu_\nu = 200\,\mathrm{MeV}$ (in the degenerate case).



dN/dE$_\nu$ (MeV^{-1})
.6
.5
.4
.3
.2
.1
0
0
50
100
150
200
250
E$_\nu$ (MeV)

Table 1: Summary of experimental results on the 17 keV neutrino.

Technique	$100\sin^2\theta$	m_2 (keV)	Authors
^3H in$^+$ Si(Li)	3 ± 1	17.1 ± 0.2	Simpson '85
^3H in$^+$ Ge	1.11 ± 0.14	16.93 ± 0.07	Hime and Simpson '89
^{35}S Si(Li)	0.73 ± 0.11	16.9 ± 0.4	Simpson and Hime '89
^{35}S Si(Li)	0.84 ± 0.08	17.0 ± 0.4	Hime and Jelley '90
^{14}C in$^+$ Ge	1.40 ± 0.45	17 ± 2	Sur, etal. '90
^{71}Ge (IBEC)*	1.60 ± 0.74	17.2 ± 1.3	Zlimen, etal.'90
^{55}Fe (IBEC)	0.85 ± 0.45	21 ± 2	Norman, etal. '91
^{63}Ni Si(Li)	0.79 ± 0.12	16.75 ± 0.50	Hime and Jelley '91
^{35}S Si(Li)	< 0.3 $(90\% CL)$	null	Ohi, etal. '85, '86
^{35}S mag. spect.	< 0.4 (99%)		Alzitzoglou, etal. '85
^{35}S mag. spect.	< 0.17 (90%)		Apalikov, etal. '85
^{35}S mag. spect.	< 0.6 (90%)		Datar, etal. '85
^{35}S mag. spect.	< 0.25 (90%)		Markey and Boehm, '85
^{63}Ni mag. spect.	< 0.3 (90%)		Hetherington, etal. '86
^{63}Ni mag. spect.	< 0.25 (90%)		Wark and Boehm '86
^{125}I inner brem. Ge	< 0.9 (90%)		Borge, etal. '86
^{55}Fe inner brem. Ge	< 0.74 (90%)		Zlimen, etal. '87
^{35}S mag. spect.	< 0.6 (90%)		Becker, etal. '91
^{177}Lu mag. spect.	< 0.2 (90%)		Schreckenbach, etal. '91
^3H proport. chmbr.	< 0.4 (90%)		Bahran and Kalbfleisch '91
^{35}S mag. spect.	< 0.85 (99.6%)		Boehm, etal. '91

$^+$Source implanted in detector.

*Inner bremsstrahlung.