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REVIEW OF NEUTRINO MASS MEASUREMENTS

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ABSTRACT

The current status of the experimental search for neutrino mass is reviewed, with emphasis on direct kinematic methods. New data on the τ neutrino from the Argus collaboration have reduced the upper mass limit a factor of 2. The situation concerning the electron neutrino mass as measured in tritium beta decay is essentially unchanged from a year ago. Simpson and Hime report finding evidence for a 17-keV neutrino in the β decay of ^{35}S. There may be evidence for neutrino mass and mixing in the SN1987a data.

1. INTRODUCTION

The continuing intensive experimental search for neutrino mass is motivated by the profound implications for cosmology and for particle physics. As is well known, the universe would be gravitationally closed by a neutrino having a mass of a few tens of eV, and the 1980 report[1] by the group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow of a 35 eV electron neutrino mass therefore aroused great interest. In the intervening 8 years, the ITEP group have improved their apparatus, taken more data, refined their analysis, and still find qualitatively the same result. The dissenting experimental voice is that of the Zürich group, who in 1985 reported[2] an upper limit of 18 eV on the mass.

While there has been no recent work on the mass of the μ neutrino, a vigorous program of research on the τ continues. The Argus collaboration at DESY has observed[3] several examples of the decay of the τ to 5 charged pions, and can set an upper limit of 35 MeV on the mass of ν_τ. This represents a substantial advance over the previous limit (also Argus[4]) of 70 MeV.

In our review we survey mainly the direct methods for determining neutrino mass, i.e. those methods that do not depend for their success on the violation of lepton family number (or lepton number). Neutrino oscillations and double beta decay are discussed by others at this meeting. We make one exception, however, and mention the new work of Simpson and Hime[5] that appears to show evidence for a small admixture of a 17-keV neutrino in the electron neutrino.

In the following, the neutrinos are identified as ν_1, ν_2, and ν_3, and their masses are m_1, m_2, and m_3. This is both to achieve a simple notation and to serve as a reminder that neutrino mass eigenstates may not necessarily be flavor (current) eigenstates. Thus ν_1 is *predominantly* the electron neutrino, etc. No distinction will be made between the masses of neutrinos and antineutrinos, their equality being assured under CPT.

2. COSMOLOGICAL CONSTRAINTS

Fortified by the remarkable successes of the standard big-bang theory, cosmologists have been able to constrain the physics of elementary particles in several unique ways. One of these results is relevant to this discussion: The sum of the masses of the stable neutrinos must be less than about 65 eV. As has been discussed by many authors[6-8], the present-epoch density of primordial neutrinos may be related directly to the 3-K microwave background

The neutrino plus antineutrino density per flavor is 109 cm^{-3}, and a neutrino mass of 96 eV is sufficient to close the universe. More generally,

$$\Sigma m_\nu = 96\ \Omega_\nu\ h_0^2\ \text{eV} \quad ,$$

where Σm_ν is the sum of all neutrino masses and h_0 the Hubble in units of 100 km s^{-1} Mpc^{-1}. This simple relationship must be modified in two respects, however. First, normal baryonic matter also fills the universe and contributes a mass density. It is one of the triumphs of big-bang nucleosynthesis that the abundances of the light isotopes ^4He, ^2H, ^3He, and ^7Li can be quantitatively explained and that a single, concordant value of the baryon density emerges from the analysis. The result[6] may be expressed as:

$$\Omega_N = (0.018 \pm 0.008)\ h_0^{-2} \quad .$$

The second modification has been emphasized by Steigman[6]: Simultaneously large values of Ω and H_0 imply an impossibly young universe and must be excluded. The age of the universe in Gy may be

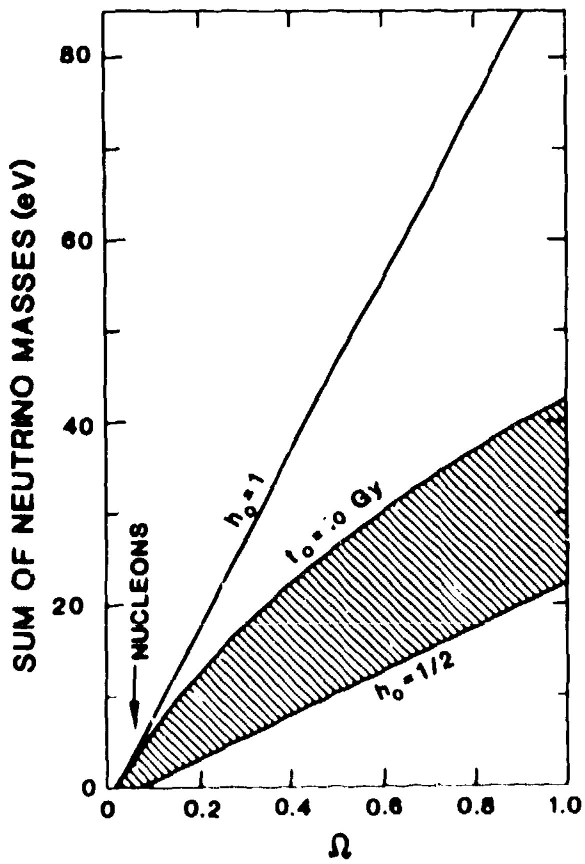

Fig.1 Allowed region (shaded) for neutrino mass, in the absence of other sources of dark matter.

written[6,8],

$$t_0 = \frac{9.78}{h_0} \int_0^\infty \frac{dz}{(1+z)^2(1+\Omega z)^{1/2}}$$

The integral varies smoothly from 1 for Ω small to 2/3 for $\Omega = 1$. The age of the universe is at least 10 Gy. Given that $\frac{1}{2} < h_0 < 1$, we may plot the allowed region for neutrino mass as shown in Fig. 1. It is clear that the allowable mass in neutrinos is severely restricted by the age of the universe -- ages longer than 10 Gy restrict the range more strongly. There is room for neutrino mass in the range suggested by the ITEP experiments[1,9] on tritium beta decay, although it would be surprising if the electron neutrino were the heavyweight.

Harari and Nir[10] have also considered the cosmological implications of massive neutrinos and find that there are possibly two allowed regions. As before, stable neutrinos are confined to be lighter than 65 eV (values of Ω up to 2 are observationally not ruled out). In addition, there may be a window for unstable neutrinos above 1 MeV. Since this is above the laboratory limits for the masses of ν_1 and ν_2, only the tau neutrino is a candidate (among known particles). Recent experimental work on the τ neutrino has narrowed this window.

3. MASS OF ν_μ AND ν_τ

Experiments on the μ and τ neutrinos have not yielded evidence of finite mass. For ν_μ the best limit comes from measurement[11] of the momentum of muons emitted by π^+ decaying at rest -- the upper limit for the ν_μ mass is 250 keV. A more detailed discussion of this limit is presented elsewhere[12], but it is germane to point out that it depends sensitively on the mass of the charged pion. That mass is generally determined from pionic atoms and there are potentially important theoretical uncertainties in the radiative and strong interaction corrections. The result obtained by Abela et al.[11],

$$\langle m_2{}^2 \rangle = -0.163(80)\ \mathrm{MeV}^2,$$

has a rather low probability (2%) of having arisen statistically, and probably reflects a problem with the pion mass. Jeckelmann et al.[13] have carried out a new measurement of the pion mass (unfortunately overlooked in ref. 12) that substantially improves the situation:

$$\langle m_2{}^2\rangle = -0.097(72)\ \mathrm{MeV}^2.$$

The upper limit on m_2 is not significantly changed, however: $m_2 < 270$ keV at 90% CL under the prescription recommended by the Particle Data Group[14] (Confidence levels on quantities confined to a physically allowed region are complicated -- for a discussion see ref. 12). Measurements less dependent on the pion mass are those of Anderhub et al.[15] and Clark et al.[16]

Several investigations of the ν_τ mass have been carried out, the one giving until recently the lowest limit (70 MeV) being the Argus measurement[4] of the decay of the τ to three charged pions and ν_τ. This year the same collaboration has reported[3] the observation of 12 events in which a τ decays to 5 charged pions and ν_3. In principle, the derivation of a neutrino mass from this type of experiment requires an a priori knowledge of the invariant mass distribution of the pions, but in this case two events lie so close to the mass of the τ that the neutrino mass can be constrained in a virtually model independent way to less than 35 MeV (95% CL). This important result reduces the cosmologically allowed area for unstable τ neutrinos in the Harari-Nir[10] analysis.

4. TRITIUM BETA DECAY EXPERIMENTS

As is well known, the ITEP group in Moscow has reported[1] since 1980 that the electron antineutrino has a mass of about 35 eV (now revised[9] to 26 eV). The method is a careful study of the beta spectrum from tritium decay:

$$N(E) = C\ F(Z_f,R,E)\ p_e\ E\ \Sigma_i w_i (E_0-E_i-E)[(E_0-E_i-E)^2-m_\nu{}^2c^4]^{1/2}$$

$$\times\ [1+\alpha_1(E_0-E)+\alpha_2(E_0-E)^2] \quad ; \quad E \le E_0-E_i-m_\nu c^2$$

where $F(Z_f,R,E)$ is the Fermi Coulomb distortion factor, a smoothly varying function of energy. The total energy is E_0. Weak magnetism and nuclear recoil give[17] α_1 a value of 2.312×10^{-9} eV^{-1}. The summation is over all final states of the daughter system. Each final state has a different energy, and calculating the energies E_i and branching ratios w_i to the final states is a matter of fundamental importance in all tritium experiments. Equally important, but more amenable to experimental checks, are energy loss as the electron traverses the source material, instrumental resolution, and backscattering.

The development of tritium beta decay studies has been reviewed frequently[12,18]. Lyubimov has described the status of the ITEP work at this meeting. We will not repeat the historical material, but mention only recent work and prospects for the future.

The ITEP group has continued to improve the apparatus and the analysis. Most recently, the ITEP group became concerned about the large discrepancy between the variance of the final state spectrum for valine actually used in the 1985 analysis, 697 eV^2, and the sum-rule value, 1282 eV^2, recently obtained by Kaplan & Smelov[19]. In previous analyses the continuum in valine had been represented by a single state that gave the correct normalization and average excitation energy. They replaced the single state in the continuum with two, so positioned as to reproduce the first three moments correctly. Power-law distributions were also tried. The result[9] of a reanalysis of the 1985 data augmented with some new data was to decrease the neutrino mass slightly to 26(5) eV (no CL given). The "model-independent" lower limit, established from the endpoint energy as described below, remained at 17 eV.

In preparation for a new cycle of experiments, the resolution of the spectrometer has been improved from 20 eV to about 15 eV by reducing the size of the slit in front of the proportional counters from 0.8 to 0.5 mm. To avoid a concomitant loss of data rate, the spacing between the counters has been reduced from 4 to 2 mm. Electrons are not fully stopped in such a small detector and it remains to be seen whether the efficiency and background rate will be satisfactory. The valine source material now has 6 tritium atoms per molecule instead of 2, and the thickness has been reduced a factor of 3. It will be most interesting to see the effect of these improvements.

The Zürich group reported[2] in 1985 an upper limit of 18 eV, in some conflict with the ITEP result. Since then, they have concentrated on reducing the background in their apparatus, much of which arises from tritium leaving the source material (tritium-implanted carbon) and migrating around in the spectrometer. Both the source and spectrometer are now cooled with the intent of reducing the mobility of the tritium. Thinner implanted sources with a no-loss fraction of 80% are being prepared, and Langmuir-Blodgett films are under development.

A puzzling feature of the disagreement between the ITEP and Zürich works was the substantial difference in the energy-loss spectra (see ref. 12). The Zürich group had calculated the energy loss using a plasmon model, while ITEP had measured it by depositing different thicknesses of source material on a calibration source. At the INS International Symposium on Neutrino Mass and Related Topics in Tokyo earlier this year, W. Kündig of the Zürich group reported[20] that the energy loss spectrum was underestimated by a factor of 2, which would approximately reconcile the difference between ITEP and Zürich. However, at the same time the source thickness was overestimated by a factor of 2, and the Zürich result is therefore reportedly unchanged.

Following initial publication[21] of a 32-eV upper limit the group at the Institute for Nuclear Studies (INS), Tokyo, have brought[22] the total statistics in the last 100 eV to 14000 from 5000. The shakeup and shakeoff spectrum of ^{109}Cd, needed to derive the instrumental resolution, was obtained by making measurements with two different source thicknesses and unfolding the energy loss contribution. Backscattering was found by examination of the spectrum far below the ^{109}Cd KLL Auger lines to be negligible . The final state spectrum of valine calculated by Kaplan and collaborators[23] was used for the arachidic acid source. The previous data set gave $m_1{}^2 = 287(341)$ eV^2, and the more recent set $m_1{}^2 = 155(349)$ eV^2. The weighted mean is $m_1{}^2 = 223(244)$ eV^2. The uncertainties are statistical only. With the inclusion of systematic uncertainties, the upper limit from the INS work is now 28 eV.

In the future, the INS group plans to use a new, larger source and a larger position-sensitive detector to achieve a 30-fold increase in data rate. Through compensation of third-order aberrations, it is expected that a 2 eV FWHM resolution can be achieved. This will be truly remarkable performance for a magnetic spectrometer, and the main limitation in the neutrino mass determination will likely be uncertainties in the final-state spectrum.

The Los Alamos experiment[24], in which a source of gaseous T_2 is used, produced an upper limit of 27 eV at the 95% CL. The accuracy of the result was limited almost entirely by statistics, and the Los Alamos group has concentrated on improving the data rates. The single-element proportional counter at the focus of the spectrometer has been replaced by a 96-pad Si microstrip array. This has resulted in an improvement of a factor of 7.8 in the gross data rate and 2.7 in the signal-to-noise ratio. Furthermore, during these measurements, the spectrometer acceptance was restricted in order to obtain a resolution improvement of about 30%. Data-taking with the new system has commenced. In the future the Los Alamos group intends to measure the K-shell photoionization spectrum of Kr in order to reduce the uncertainties associated with the shakeup and shakeoff satellites of $^{83}Kr^m$. That isotope is used to determine the spectrometer response function.

Other groups are continuing to make progress. The Oxford experiment[25] makes use of a cylindrical mirror analyzer and a Cd-palmitate-T source. Initial tests show 15 eV resolution and a background rate of only 8 hr^{-1}. With an iron-core spectrometer and a Langmuir-Blodgett source, the group at the Institute for Atomic Energy in Beijing reports[26] a preliminary upper limit of 30 eV on m_1. Two new experiments with gaseous T_2, one[27] utilizing a toroidal magnetic spectrometer at Lawrence Livermore National Laboratory (LLNL), and the other[28] a magnetic-electrostatic retarding potential analyzer at the Institute for Nuclear Research in Moscow, are expected to begin operation shortly. At the Yorktown Heights laboratories of IBM, Clark and Frisch[29] will make use of a metal tritide source and an electrostatic retarding-potential analyzer. Source-in background rates have been reduced to a satisfactory level. Three groups, at LLNL[30], at the University of Mainz[31], and at the Ohio State University[32], are working on frozen T_2 sources.

5. THE ^3H - ^3He MASS DIFFERENCE

The neutrino mass is derived only from the shape of the β spectrum and is thus independent of the endpoint energy. Nevertheless, the endpoint energy is a fitted parameter whose value may be compared with other determinations of the mass difference between ^3H and ^3He. It thus serves as a check (one of very few available) on some kinds of systematic error.

It may be shown[12] that the experimental endpoint energy found by fitting data from lower energies with no assumption about the final-state spectrum is

$$E_{exp} = E_0 - \langle V_i \rangle,$$

where E_0 is the endpoint energy for the transition to the lowest final state and $\langle V_i \rangle$ is the average excitation energy of the residual molecule. The atomic mass difference, $\Delta M = M(^3H) - M(^3He)$, is then given by

$$\Delta M = E_{exp} + \langle V_i \rangle - B(T) + B(He) - B(R{:}He^+) + B(R{:}T) + E_{rec},$$

where B(x) is the atomic binding energy of the molecule x. (Generally it is $E_0 = E_{exp} + \langle V_i \rangle$ that is quoted by experimental groups as the "endpoint energy".) The recoil energy E_{rec} is about 3.4 eV.

Hence, the experimental endpoint energy is related to ΔM through the first moment $\langle V_i \rangle$ of the final-state distribution, whereas the derived neutrino mass depends mainly on the second moment. The ITEP collaboration, recognizing that there is some uncertainty in the final-state spectrum, have explored the effect of using a variety of different theoretical spectra. Both the first and second moments are altered, and at some point the good agreement between the ΔM from the ITEP[9] tritium spectrum [18599(4) eV] and from the ion-cyclotron-resonance work of Lippmaa et al.[33,34] [18599(2)] is lost. The ITEP group argue[35] that the point where these disagree at the 1.3SD level constitutes a model-independent limit on possible variations in the final-state spectrum, and find a range of 17 to 40 eV for m_1. The necessary precision in ΔM is very high -- a 6-eV change would be sufficient to reduce the lower limit on m_1 from 17 eV to 0. As may be seen in Fig. 2, the experimental picture on the ^3H - ^3He mass

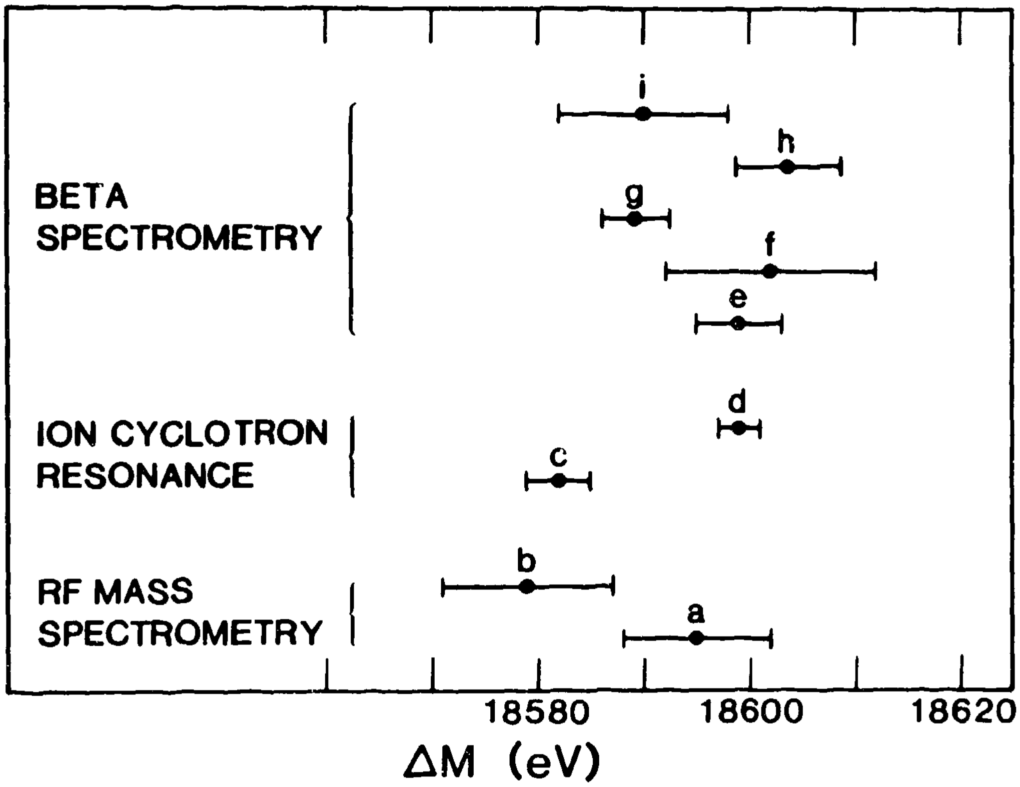

Fig. 2. Determinations of the ^3H - ^3He mass difference ΔM. a,b: ref. 37; c: ref. 38; d: refs. 33,34; e: ref. 9; f: ref. 2; g: ref. 39; h: ref. 22; i: ref. 40.

difference is rather unsatisfactory, with several precise measurements in serious disagreement. Moreover, this test, while informative, does not lead to a completely model-independent limit inasmuch as the first and second moments of distributions are not functionally related. Nevertheless, the usefulness of the kind of comparison made by ITEP for disclosing systematic problems cannot be overstated, and it is to be hoped that direct determinations of ΔM at the 1 eV level will soon be made.

6. THE 17-KEV NEUTRINO

In 1985 Simpson[41] reported that there was at the low-energy end of the tritium beta spectrum a distortion indicative of a 3% admixture of a 17.1-keV antineutrino with the dominant electron antineutrino. It was subsequently shown by Lindhard and Hansen[42] and by Eman and Tadic[43] that about 67% of the distortion could be explained by Simpson's use of an incorrect screening potential. A similar effect, exchange between the orbital electrons and the outgoing beta particle, was noted by Haxton[44] to be responsible for another 15% of the distortion. Thus, the remaining evidence from beta decay of tritium in Si for a 17-keV neutrino, if any, seems too model-dependent to be conclusive.

The 18.6-keV Q-value for tritium beta decay makes it a poor candidate for revealing a 17-keV neutrino, and several groups took up the search in ^{35}S (Q = 167 keV) and ^{63}Ni (Q = 67 keV). In ^{35}S five groups claimed[45-49] to find no evidence for a 17-keV neutrino at levels below that found by Simpson, but Simpson[50] rebutted three of those claims by pointing out that the analyses had been done incorrectly (the data sets had only been fitted under the assumption of no second neutrino, and not with full variation of all allowed parameters). Indeed, in one case, there was a better fit when a 1 to 2% admixture of a 17-keV neutrino was included, and in other cases the upper limits were no longer sufficiently stringent to be interesting. Most difficult to dismiss, however, is the very detailed study of ^{63}Ni carried out by Hetherington et al.[51], in which an upper limit of 0.3% (90% CL) was set on the heavy neutrino admixture.

Simpson and Hime[5] now report not only that the beta spectrum of tritium implanted in Ge shows the effect of a heavy neutrino admixture, but also that there is strong evidence in ^{35}S for the same admixture. The residuals near the ^{35}S endpoint are shown in Fig. 3. From these data, Simpson and Hime conclude that there is a 0.8(1)% admixture of a 16.9(4)-keV neutrino. While the effect is unmistakably present (and not likely to be a statistical fluke), the question is, does it represent a heavy neutrino admixture or some less exciting physical effect? Judgment on this matter will have to await

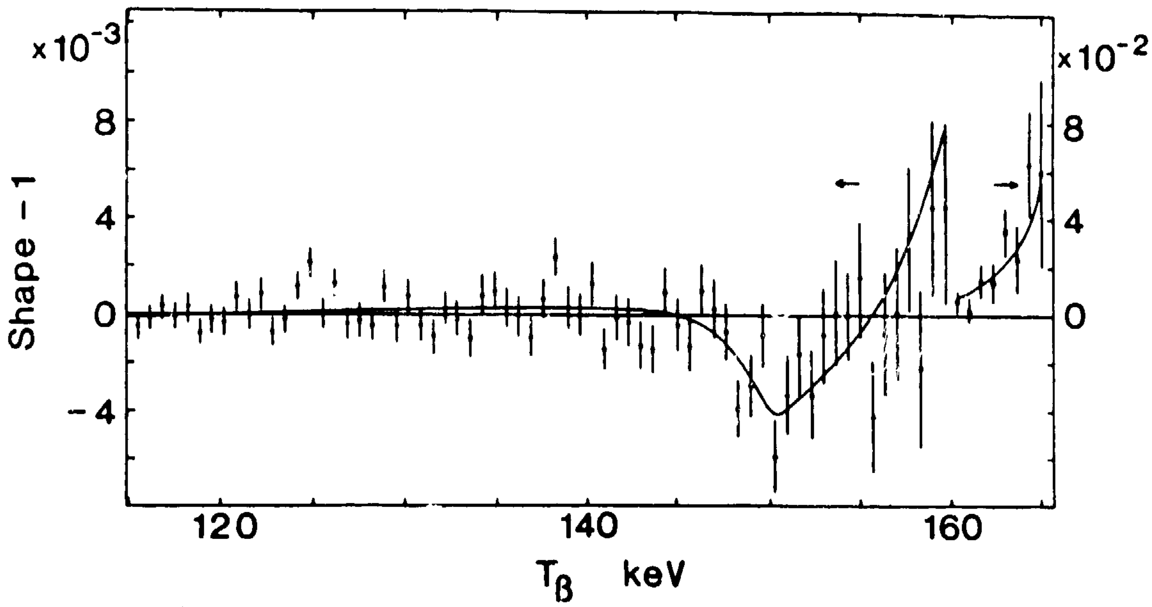

Fig. 3. Data of Simpson and Hime (ref. 5) on the β decay of ^{35}S. Residuals are shown relative to a straight line (the expected shape for zero neutrino masses) and a curved line (the expected shape if there is a 1% admixture of a 17-keV neutrino).

presentation of the detailed account of the experiment, but one may note already that the thickness of the backing of the source is large enough to require very careful corrections that do not at present seem to have been made. Electrons can enter the backing and reemerge with an energy loss that averages about 10 keV and falls off rapidly above 20 keV. Perhaps such a backscattering component could produce a distortion in the spectrum resembling a 17-keV neutrino.

7. SUPERNOVA SN1987a*

The historic observation[52-55] of neutrinos from the supernova SN1987a in the Large Magellanic Cloud on February 23, 1987, provided a new window on neutrino physics and astrophysics. Among the many interesting physics questions to be addressed was that of neutrino mass. Space does not permit us to do justice to the enormous literature on this topic, but most works have sought to demonstrate that the mass of the electron neutrino must be quite small. Limits ranging from a fraction of an eV to about 15 eV have been published.

*Not included in oral presentation.

Kolb, Stebbins, and Turner[56] have emphasized the need for caution in such analyses in light of the considerable model dependence that is inherent when little is known about the temporal and thermal evolution of a supernova and the particle properties of neutrinos. Nevertheless, a careful statistical analysis by Spergel and Bahcall[57] appears to show conclusively that, at the 95% CL, a mass m_1 greater than 16 eV can be ruled out. It is stated that this limit is substantially better than terrestrial measurements.

Because of the influential nature of this latter paper (and an earlier one claiming an 11-eV limit[58]), we thought it appropriate to draw attention to an alternative interpretation that has been advanced by at least four groups[59-62]. If neutrinos have mass, then neutrino mixing is possible, even likely. The events in the water Cherenkov detectors are, with one possible exception, charged current interactions on the proton induced by "electron antineutrinos". There may be three (or more) mass eigenstates with some electron current component, and they will propagate at different velocities. The arrival time t_i (s) for a neutrino of mass m (eV), energy W_i (MeV) from the LMC is

$$t_i = T_0 + d_{LMC}\, m^2/W_i^2,$$

where d_{LMC} is 2.68(26) in these units[56], and T_0 is the arrival time for a massless particle. On a log-log plot of W_i vs $t_i - T_0$, events will fall on straight lines of slope -1/2 if neutrino mass is the source of the dispersion. Fig. 4 shows that plot with all known data in the vicinity of 7:35 UT (from Kamiokande II[52], IMB[53], Baksan[54], and Mont Blanc[55]) on it. The 30 points are fit with 5 parameters:

T_0	7:35:40.90
Kamiokande first event	7:35:41.20
Baksan first event	7:35:41.15
m_1	6.1 eV
m_2	26.0 eV

One can see that this hypothesis organizes the data in a very striking fashion. There appears to be no conflict with known limits on oscillations if the two groups correspond to ν_1 and ν_3, and it may even be possible to accommodate ν_2 as the lighter neutrino. The plot

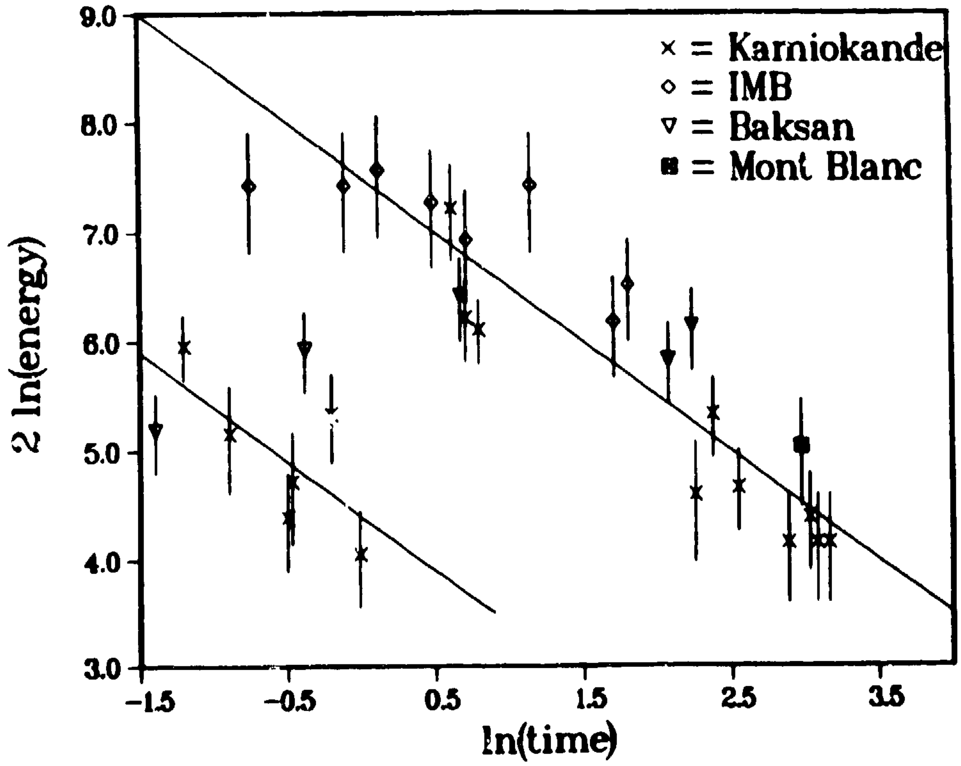

Fig. 4. Log-log plot of neutrino arrival time against neutrino energy. The upper line corresponds to a neutrino mass of 26 eV and the lower one 6 eV.

shown here is qualitatively the one originally given by Lyubimov[62]; others find slightly different values for the two masses. The time evolution of the supernova is ignored in all these studies, and needs to be considered. A decay time of a few seconds has no effect on the upper branch, but eliminates the indication for nonzero mass in the lower branch. Longer times affect the upper branch, progressively reducing the mass.

It would be hazardous to hold that this argument "proves" neutrinos have mass, but it does cogently demonstrate that, from SN1987a, there is no basis for a limit on the electron neutrino mass smaller than about 30 eV.

8. CONCLUSION

The controversy surrounding the mass of the electron neutrino remains unresolved. A limit of 27 eV (95% confidence level) on the mass has been set[24] that is relatively free of model assumptions, but it is not in conflict with either the positive ITEP result[9], 26(5) eV, or the null Zürich result[2], $m_1 < 18$ eV, both of which are model dependent. The neutrino data from supernova SN1987a does not rule out an electron neutrino mass smaller than about 30 eV, and[56,59-62] may even favor one in the range 20 to 30 eV. Experimental upper limits on the masses of the μ and τ neutrinos are 270 keV (90% confidence level) and 35 MeV (95% confidence level), respectively.

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