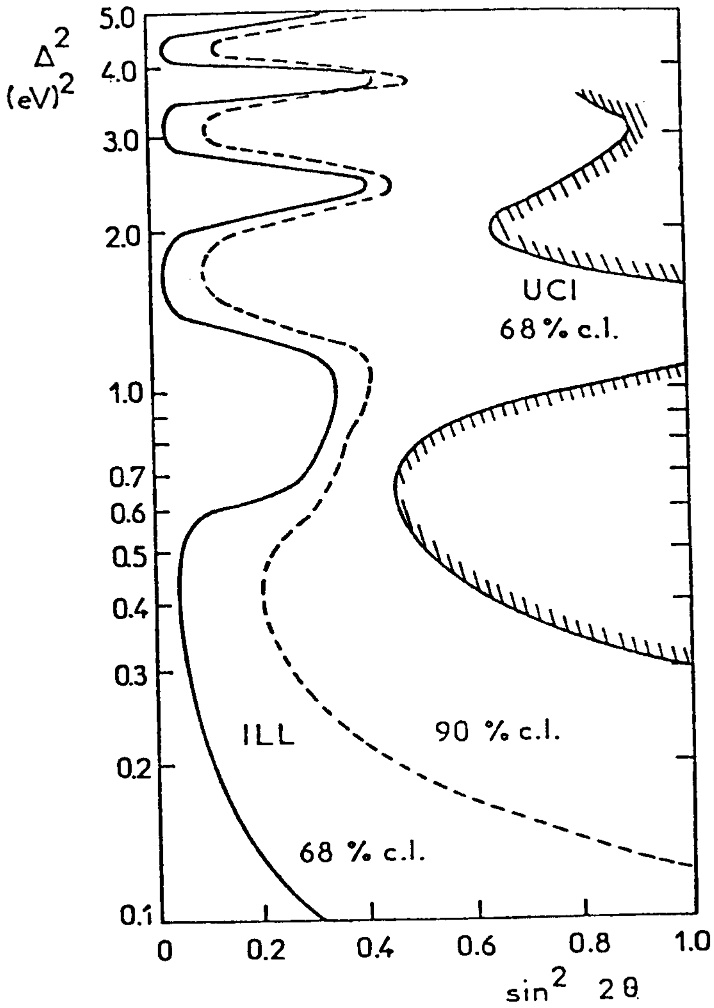

Fig. 7. The limits of the neutrino oscillation parameters. The ILL curves refer to the ccp reaction at 8.7 m^6; the allowed region is to the left of the curves. The UCI curves refer to the ccd/ncd ratio[1]; the allowed region is to the right of the curves.

THE GRENOBLE NEUTRINO OSCILLATION EXPERIMENT

Presented by

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ABSTRACT

The electron-antineutrino induced positron spectrum has been measured at an 8.75 m position from the "point-like" core of the ILL ^{235}U fission-reactor, using the reaction $\bar{\nu}_e + p \rightarrow e^+ + n$. Positrons and neutrons were detected in coincidence by means of a liquid scintillator and ^3He detector system. The currently observed positron spectrum is consistent with theoretical predictions assuming no neutrino oscillations. Upper limits for the oscillation parameters are presented.

INTRODUCTION

The possibility for the occurence of neutrino oscillations and the related question of neutrino rest masses has been of great concern in recent years[1, 2]. We report here on the current status of the neutrino experiment at the research reactor of the Institut Laue-Langevin (ILL). The goal of our study is to measure the energy spectrum of electron-antineutrinos ($\bar{\nu}_e$) emitted following the fission of ^{235}U in order to search for neutrino oscillations of the type $\bar{\nu}_e \rightarrow$ anything. The present experiment measures the energy dependence of the antineutrino yield at a fixed distance d = 8.75 m. The possible existence of neutrino oscillations is of particular interest in connection with the solar neutrino puzzle[1], cosmological considerations[3], and the fundamental structure of leptonic currents[1, 2].

GENERAL CONSIDERATIONS

Neutrino oscillations of the weak interaction eigenstates (ν_e, ν_α,...) may occur if these "physical" neutrinos are superpositions of the mass eigenstates (ν_1, ν_2,...). If we confine our discussion to the case of a two-neutrino system (which might well approximate the general case), the superposition can be written as

$$\begin{pmatrix} \nu_e \\ \nu_\alpha \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \end{pmatrix} \qquad (1)$$

where θ is a mixing parameter. This description[1, 2] allows for flavor oscillations ($\nu_\alpha = \nu_\mu, \nu_\tau, \ldots$) as well as for particle-antiparticle oscillations ($\nu_\alpha = \bar{\nu}_{eL}, \ldots$ where L stands for lefthanded). The time development of the system in eq. (1) is given by

$$|\nu_e(t)|^2 = |\nu_e(0)|^2 \left[1 - \frac{\sin^2(2\theta)}{2}\,(1 - \cos\,(E_2 - E_1)t)\right]$$

where E_i is the energy of the neutrino ν_i. For momenta $p >> m_i$ (m_i being the mass) $E_2 - E_1 \approx (m_2^2 - m_1^2)/(2p)$.

The oscillation length Λ (in meters) is related to the neutrino kinetic energy E_ν (in MeV) and to the mass squared difference $\Delta^2 = |m_2^2 - m_1^2|$ in $(eV)^2$ by

$$\Lambda = 2.48\, E_\nu/\Delta^2. \qquad (2)$$

The oscillations are thus characterized by the parameters Δ^2 and $\sin^2(2\theta)$.

The counting rate Y in a $\bar{\nu}$-detector at a distance d from an antineutrino source (reactor core) is (using the same units) given by

$$Y(E_{\bar{\nu}}', \Delta^2 d) = \varepsilon N(E_{\bar{\nu}}')\sigma(E_{\bar{\nu}}') \left[1 - \frac{\sin^2(2\theta)}{2}\,(1 - \cos(2.53\Delta^2 d/E_{\bar{\nu}}))\right] \qquad (3)$$

where $N(E_{\bar{\nu}})$ is the reactor produced $\bar{\nu}$-spectrum and ε is the detection efficiency. The cross section $\sigma(E_{\bar{\nu}})$ (with $E_{\bar{\nu}}$ in MeV) of the detector reaction is given by[4]

$$\sigma(E_{\bar{\nu}}) = (9.13 \pm 0.11)(E_{\bar{\nu}} - 1.293)\sqrt{(E_{\bar{\nu}} - 1.293)^2 - (0.511)^2}\ 10^{-44}\,\text{cm}^2. \qquad (4)$$

Here a neutron lifetime of τ_n = (926±11) s[5] has been used.

As can be seen from eq. (2), reactor experiments ($E_{\bar{\nu}}$ < 10 MeV, d < 100 m) are suitable to study mass squared differences in the range of $0.01 < \Delta^2 < 5$ $(eV)^2$ for sufficiently large mixing angles. Previous published limits for the parameter Δ^2 in the channel $\nu_\mu \leftrightarrow \nu_e$ (assuming full mixing) are in the vicinity of $\Delta^2 \lesssim 1$ $(eV)^2$ (90% c.l.)[6-8]. However, experiments at CERN and Serpukhov which explored different channels might be interpreted as suggesting non-vanishing values of Δ^2 and large mixing angles[2, 9, 10]. Recently, Reines et al.[11] have reported evidence for non-zero oscillation parameters, in a study of the reactions $\bar{\nu}_e + d \rightarrow \bar{\nu}_e + p + n$ and $\bar{\nu}_e + d \rightarrow e^+ + n + n$.

METHOD AND APPARATUS

The ILL reactor (57 MW; 93% ^{235}U) has been chosen as the antineutrino source, because the small size of its core (40 x 80 cm) makes it suitable for the study of very small oscillation lengths. A neutrino flux of 0.98×10^{12} $cm^{-2}s^{-1}$ is available at our detector position. The inverse beta decay $\bar{\nu}_e + p \rightarrow e^+ + n$, which has a threshold energy of 1.8 MeV, is used as the detection reaction[12].

The central detector consists of 30 lucite cells filled with a total of 377 l of proton-rich liquid scintillator (NE235C*; ρ = 0.86 g cm^{-3}; H/C = 1.71) arranged in five vertical planes. Four ^{3}He wire chambers at atmospheric pressure are sandwiched between the scintillation counters, as shown in Fig. 1. The scintillator cells serve as proton target, positron detector and neutron moderator. The dimensions of the target cells were chosen to optimize neutron moderation, light collection and minimize neutron absorption. The central detector is surrounded by a liquid scintillator veto and various shieldings, as depicted in Fig. 1. Efficient discrimination against proton recoil pulses initiated in the target cells by fast neutrons of cosmic-ray origin is achieved by means of pulse shape discrimination(PSD). A typical rejection rate of 98% is obtained (with only 2% loss of the positron signal). The energy resolution of the target cell is 18% FWHM at 1 MeV. Absolute energy

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Table I The count rates of the detector components sampled during 24 hours before and after the full power operation of the reactor.

Reactor Status	count rates (counts/sec)			
	30 target cells*	4 ^{3}He counters**	6 veto tanks*	4 umbrellas*
OFF	216.3	.422	256.8	440
ON	216.7	.427	258.6	5384

* counts above the hardware threshold
** counts above the software threshold

calibration was done with the 4.43 MeV gamma ray from $^{12}C^*$ emitted by an Am(Be) source. The advantages of the ^{3}He neutron counter are the high neutron efficiency and the low gamma background. The background rate in each ^{3}He counter from natural activities is about 0.75 counts/min in our energy window.

The neutron detection efficiency was measured by using a calibrated Sb(Be) source which emits neutrons of about 20 keV, closely approximating the actual neutron spectrum. The source could be moved to different positions within the detector volume. The total efficiency was found to be (19.5 ± 1.7)% for e^+-neutron coincidence events falling into a 200 μs time window. This rather long time window is necessary to allow for an efficient migration of the moderated neutrons to the ^{3}He detectors (80% acceptance).

DATA ACQUISITION AND ANALYSIS

Various rates of the detector components are shown in Table I demonstrating that our shielding arrangement effectively eliminates any reactor associated background. The large difference of the umbrella rates (umbrella is outside the lead shield) is due to the gamma activity of the experimental site.

The tagged signals from veto counters and target cells are stored in a buffered and continuously cycling multichannel ADC. An accepted ^{3}He signal (in the proper energy window) causes the ADC to transfer into a PDP 11 the energy, time and tagword of three preceeding target-cell events.

By recording extra two preceeding target cell events, we concurrently measure the accidental component of the background. (Notice that the mean time interval between the target cell events is 4.5 ms whereas the neutrino induced reaction is completed within 200 μs.)

Measurements were taken during five reactor-on cycles interspersed with background runs during five reactor-off periods.

Gain stability checks and adjustments are performed every three days, employing an external Am(Be) source. This procedure insured counting rate stabilities of our detector system to within 1% over the entire measurement period.

Various conditions are imposed to suppress backgrounds originating from various sources. The selection of the good events is made as follows:

1) Reject the target cell event if it occurred in more than one cell (above 850 keV hardware threshold).
2) Reject a multi ^{3}He event since there is only one neutron created by a neutrino event. These events are rare (0.05 c/min).
3) Reject a ^{3}He event outside the energy window, to suppress the gamma-ray background and the electronic noise at low energy and the alpha background at high energy. This condition reduces the total ^{3}He counting rate from 25 counts min^{-1} (the rate of the data acquisition) to 11 counts min^{-1}. Most of the eliminated events are due to alpha activity in the ^{3}He counters.
4) Reject a ^{3}He event occurring in a plane not adjacent to the plane of the first previous target cell event. This condition cuts down the accidental background by a factor of 2.5 which can be seen from a geometrical argument. The reason that this condition can be imposed is that the neutrons created in the reaction cannot travel far without being absorbed. The probability that the neutron crosses another target plane and is detected by the next ^{3}He counter is very small (less than 0.5%).
5) Reject a ^{3}He event which is in coincidence with the long veto (320 μs). It rejects the neutrons, created in the shielding and in the detector by cosmic rays, which diffuse into the system. It cuts the total ^{3}He counting rate from 11 min^{-1} to 4 min^{-1}.

6) Reject the first previous target cell event in coincidence with a short veto or a short umbrella signal (10 μs). It suppresses the bremsstrahlung events caused by decay electrons of cosmic muons stopped in the shielding. For correlated neutron-gamma ray events, it overlaps with the long veto rejection. In addition, owing to the umbrellas alone, it reduces the fast neutron rate by a factor of 2.
7) Reject a ^{3}He event which comes more than 200 μs after the target cell event. This is the time window used in the analysis which accepts 80% of the neutrino induced events. This window is a compromise between good efficiency and signal to background ratio.
8) Reject an event if the two previous target cell events are separated by less than 300 μs. This condition was first imposed since it would not be known which of the two is the positron event. It was found later that this condition reduces the background below 2 MeV by a factor of 2. From the study of the double and the triple target cell events in coincidence with a ^{3}He event, the energy spectrum of those rejected events shows a Compton edge around 2.2 MeV from neutron capture on protons. These events are caused presumably by multiple neutron events created by cosmic rays in the shielding. For example, two neutrons are captured by protons in the target cells making 2.2 MeV gamma rays while a third one enters the ^{3}He counter.
9) Reject neutron (recoil proton) events of the first previous target cell events using the PSD. The PSD cut is made such that the acceptance of the positron event, A(PSD), is 98%.

The dead times caused by above software cuts are 15% and 20% for reactor off and on respectively. All the spectra are corrected to live times.

RESULTS AND DISCUSSION

After all the above cuts are made, the energy spectra for reactor on and off are obtained and shown in Fig. 2. A comparison of the measured reactor on/off singles rates (Table I) and a differential shielding test has shown that the reactor associated background contributes at most less than 1% of our positron signal rates. As a result the positron spectrum is obtained simply by subtracting the reactor-off spectrum from the reactor-on spectrum as shown at the bottom of the Fig. 2. The signal to background ratio is better than 1 : 1 above E_{e^+} = 2 MeV. A total number of 3958 ± 158 neutrino-induced events with E_{e^+} > 1 MeV has been observed, with an average counting rate of (1.56 ± 0.07)/h.

Calculations of neutrino spectra from fission products have been published by Davis et al. (DVMS)[14] and by Avignone and Greenwood (AG)[15]. The theoretical positron spectra based on these predictions, assuming no oscillations, are likewise shown in Fig. 2. For ^{235}U fission, the AG spectrum is about 30% higher than the DVMS spectrum, the difference presumably being due to the different nuclear model assumptions used to calculate the unknown short-lived beta decays.

Two recent developments tend to favor the DVMS spectrum. The electron spectrum from fissioning ^{235}U was measured on-line at the ILL[16]. The shape was determined to better than 3%, with the uncertainty on the normalization being 7%. The DVMS spectrum agrees with that measured spectrum to better than 5%. Recent results from Oak Ridge[17] seem to confirm these findings. The present data will therefore be discussed on the basis of the DVMS spectrum.

Our experiment gives an integrated yield (for E_{e^+} > 1 MeV) of

$$\int Y_{exp}(E)dE/\int Y_{DVMS}(E)dE = 0.89 \begin{array}{l} \pm\ 0.04 \text{ (statistical error)} \\ \pm\ 0.14 \text{ (systematic error + theoretical uncertainty).} \end{array}$$

This ratio is consistent with 1.0 and is thus consistent with no oscillations. A more detailed comparison between our experimental points and the theoretical predictions for different oscillation parameters is presented in Fig. 3. The points represent the ratios of the measured to the theoretical yields for zero oscillation, corrected for finite energy resolution and core and detector size. The error bars are statistical errors only. The dotted lines give the theoretical curves for different sets of oscillation parameters. An estimated maximum uncertainty of 14% is explicitly shown in the figure for the case of zero oscillation. The present positron energy spectrum is consistent with zero oscillation.

Fig. 4 shows the upper limits for the parameters Δ^2 and $\sin^2(2\theta)$ obtained from a χ^2 test to our experimental data as well as the results from ref.[11]. Curves for 90% and 68% confidence level are shown. A limit of

$$\Delta^2 < 0.14\ (\text{eV})^2\ (90\%\ \text{c.l.})$$

for maximum mixing is obtained. For smaller mixing angles the upper limit for Δ^2 increases correspondingly.

For example, the parameters $\Delta^2 = 2.4\ (eV)^2$ and $\sin^2(2\theta) = 0.3$ shown in Fig. 3 are consistent with our data. For very large values of Δ^2, owing to the finite energy resolution, one averages over the oscillation periods and our results then give only information on $\sin^2(2\theta)$. We obtain for $\Delta^2 \to \infty$, $\sin^2(2\theta) < 0.58$ (90% c.l.). The experimental limits reported in ref.[6-8] are consistent with our results, however, one should keep in mind that these experiments sample different oscillation channels. The large mixing ratios implied by the results of ref.[11] (see caption to Fig. 4) are inconsistent with our results at the 90% confidence level.

FUTURE PROSPECTS

A continuation of the present measurements employing improved detectors and taking data at different distances is planned to eliminate the uncertainties stemming from the present unsatisfactory status of our knowledge of the theoretical antineutrino spectrum from fission sources. By measuring at 38 m and 70 m positions from the 2700 MW Gösgen reactor (in Switzerland), it appears possible to achieve a sensitivity for Δ^2 as low as 0.02 eV^2 assuming maximum mixing. Such a project is in progress by a collaboration of CalTech, SIN (Swiss Institute for Nuclear Research), and T.U. München.

REFERENCES

1. S.M. Bilenky and B. Pontecorvo, Physics Reports 41, 226 (1978)
   H. Fritzsch, Fundamental Physics with Neutrons and Neutrinos, ed. T. v. Egidy, Inst. Physics, Bristol and London (1978), p. 117; P. Minkowski, Ibid, p.144
2. A. De Rujula et al., Report TH-2788-CERN (1979)
3. D. Schramm and G. Steigen, Phys. Letters 87B, 141 (1979)
4. H. Kwon, Thesis, California Institute of Technology, Pasadena (1980)
5. C.J. Christensen et al., Phys. Rev. D5, 1628 (1972); J. Byrne et al., Phys. Letters 92B 274 (1980)
6. J. Blietschau et al., Nucl. Phys. B133, 205 (1978)
7. S.E. Willis et al., Phys. Rev. Lett. 44, 522 (1980); P. Nemethy et al., Neutrino 80, Erice (1980), to be published
8. J.K. Bienlein et al., Phys. Lett. 13, 80 (1964)
9. F. Boehm, Rapporteur talk, Neutrino 80, Erice (1980) to be published
10. F. Dydak, Rapporteur talk, Neutrino 80, Erice (1980), to be published
11. F. Reines, H.W. Sobel and E. Pasierb, Report UCI-IOP 19-144 (1980)
12. F.A. Nezrick and F. Reines, Phys. Rev. 142, 852 (1966)
13. Caltech-ILL-ISN Grenoble-TU München collaboratio, Phys. Rev., to be published
14. B.R. Davis et al., Phys. Rev. C19, 2259 (1979)
15. F.T. Avignone and Z.D. Greenwood, Phys. Rev. C22, 594 (1980)
16. K. Schreckenbach et al., Phys. Letters, to be published
17. J.K. Dickens, private communication, Oak Ridge National Laboratory (1980)

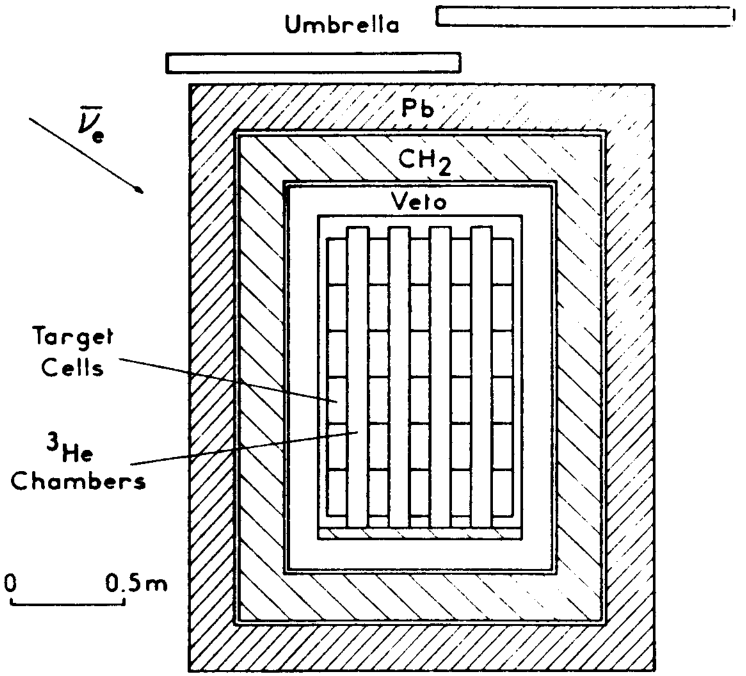

Fig. 1. Experimental arrangement. The neutrino detector consisting of 30 liquid scintillator target counters and 4 ^{3}He wire chambers is at the center. Each target counter is viewed by 4 photomultiplier tubes. 6 veto scintillation counter planes surround the detector. 4 umbrella vetos help reducing the cosmic-ray background. Lead and CH_2 shieldings are shown.

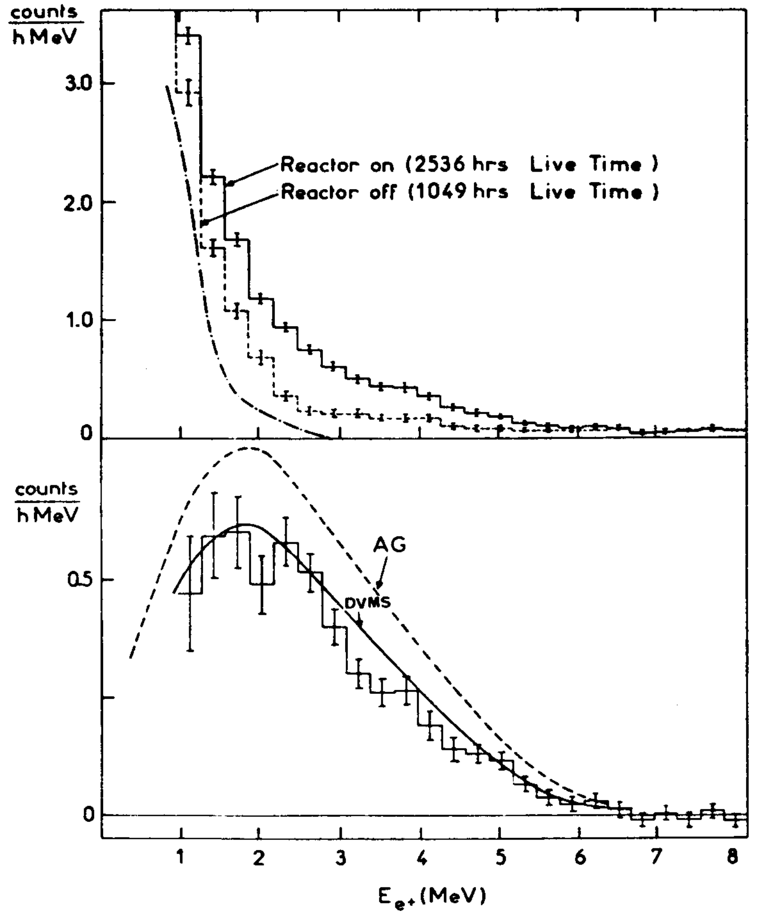

Fig. 2. Experimental results. The upper figure shows the neutron correlated e^+ spectrum for reactor on and off. No background has been subtracted. ($E_{e^+} = E_{\bar{\nu}} - 1.8$ MeV; energy bins 0.302 MeV). The error bars are statistical errors. The accidental background is shown as dot-line curve. The lower figure is the difference between the data in the upper figure and represents neutrino associated events. The error bars are statistical errors. The expected spectra, based on the $\bar{\nu}$ spectra of DVMS, ref.[14], and AG, ref.[15], corrected for detector efficiency and energy resolution are also shown.

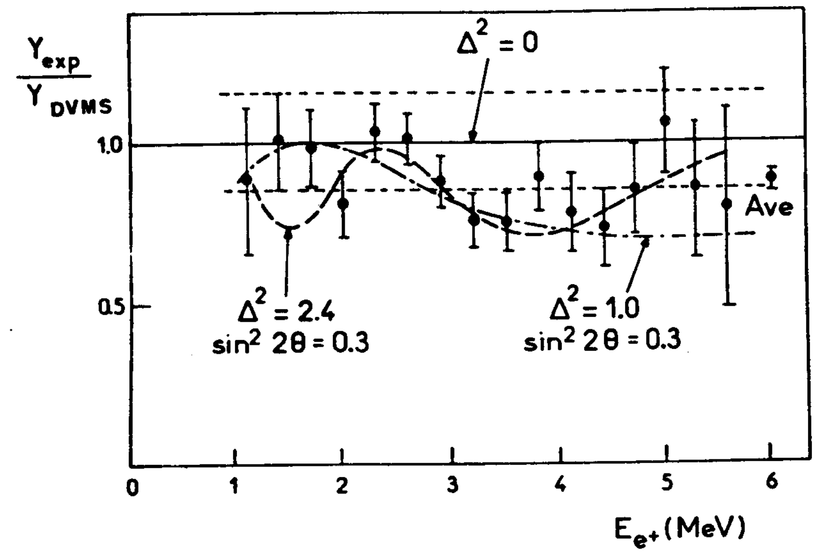

Fig. 3. Experimental e^+ spectrum normalized with the theoretical DVMS spectrum for no oscillations. The theoretical cuves (dotted lines) refer to various sets of oscillation parameters. Theoretical uncertainties and systematic errors amounting to 14% are indicated by the horizontal band for the $\Delta^2 = 0$ curve.

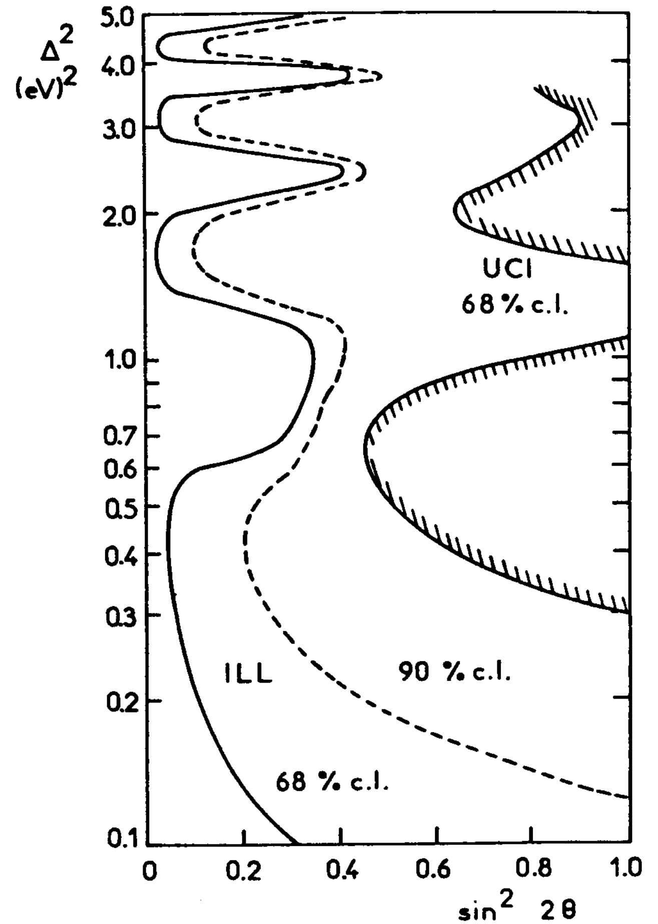

Fig. 4. The limits on the neutrino-oscillation parameters Δ^2 vs. $\sin^2 2\theta$ given by the present experiment for 68% and 90% confidence level (c.l.). The regions to the right of the curve can be excluded. The allowed regions proposed in ref.[11] are shown as a shaded area contained by the curves labelled UCI.