created by the merger of $\sim$30 smaller galaxies.[6] Further, masses as large as 100 eV would allow neutrinos to bind to individual galaxies, no longer providing the uniform background assumed above. However, it is a striking coincidence that the limit calculated here, with all the uncertainties involved, is similar to those from other cosmological considerations, and even hints from β-endpoint measurements.

ACKNOWLEDGEMENTS

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REACTOR ANTINEUTRINO SPECTRUM AND ITS IMPLICATIONS

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ABSTRACT

Calculation of the reactor associated antineutrino and electron spectra is reviewed and various theoretical spectra are compared to each other and to experimental electron spectra. The available data on reactor antineutrino induced reactions are compared to theoretical expectations. It is concluded that the charged current proton reaction results do not indicate (with one notable exception) neutrino oscillations, in contradiction to the evidence based on the deuteron disintegration reactions.

It is obvious that the only method allowing us to learn something about neutrino masses smaller than about 10 eV is the study of neutrino oscillations. Nuclear reactors are a favorable place for such a study. They provide quite a large flux of electron antineutrinos, namely

$$F(\bar{\nu}_e/\mathrm{cm}^2\mathrm{s}) \simeq 1.5 \times 10^{12}\ P/L^2. \qquad (1)$$

Here P is the reactor thermal power in MW and L is the distance to the detector in meters. Besides, the neutrino energy is small, $E = 2$-8 MeV, and the figure of merit for oscillations, L/E, is very advantageous.

There are, however, also problems. Due to the low energy one can study only the disappearance of antineutrinos. Thus in order to prove the existence of oscillations, one has to know or deduce the expected signal without oscillations. This could be achieved in three ways:

a) Use a movable detector and observe deviations (possibly energy dependent) from the $1/r^2$ dependence. Such a device will not be available for another year. Even when it becomes available, one has to know how to treat the (relatively small) time dependence of the neutrino flux related to the changing fuel composition of the reactor. Remember also that the mere constancy of the signal versus distance does not exclude oscillations completely. They could be washed out by the finite size of the reactor core or detector, or by the finite energy resolution (ΔE) of the detector. Due to the last factor one could observe only $\sim E/\Delta E$ oscillations.

b) Use another neutrino induced reaction, not affected by oscillations, as a monitor. An example is the measurement of the two deuteron disintegration reactions by Reines, Sobel, and Pasierb.[1]

c) Finally, one could deduce the expected signal from other evidence. This includes either direct calculation of the expected neutrino spectrum[2,3] or its determination from observed electron spectra accompanying beta decay of fission fragments.[4]

Table I. Electron antineutrino induced reactions studied at nuclear reactors

Reaction	Symbol	(10^{-44} cm^2/fission)[a]	Threshold(MeV)
$\bar{\nu}+p\rightarrow n+e^+$	ccp	60.0	1.8
$\bar{\nu}+d\rightarrow n+n+e^+$	ccd	1.2	4.0
$\bar{\nu}+d\rightarrow n+p+\bar{\nu}$	ncd	2.9	2.3
$\bar{\nu}+e\rightarrow \bar{\nu}+e$	cce–nce[b]	0.4	$\sim$ 1.7[c]

[a] Based on the spectrum of Ref. 2

[b] Signifies destructive interference, calculated for $\sin^2\theta_W = 0.25$.

[c] Practical threshold.

The approach a) is not available yet and the approach b) which indicates presence of oscillations, has some evident advantages. But there is a price to pay for the use of method b) as indicated in Table I; the deuteron disintegration reactions have cross sections 20 and 40 times smaller than the ccp reaction. On the other hand, a study based on method c) and ccp reaction is experimentally simpler, the neutrino events are better defined, and it is possible to measure the whole positron spectrum. Thus one can compare with expected result not only the total rate but also the spectrum shape. Three relatively accurate measurements of this type are available now at 6 m[5], 8.7 m[6], and 11.2 m[1] from the reactor core.

The calculation of the neutrino spectrum is, in principle, straightforward. The fission fragments are neutron rich and undergo on the average three beta decays each. Thus we expect about six electrons and electron antineutrinos for each fission event. To calculate the corresponding spectrum one has to add the contributions of all fission fragments <u>n</u>, and for each fragment add the contributions of all beta decay branches <u>i</u>. Thus

$$N(E_{\bar{\nu}}) = \sum_{n,i} N_{n,i}(E_{\bar{\nu}}), \tag{2}$$

where

$$N_{n,i} = Y_n(Z,A,t)\; b_{n,i}\,(E_o^i)\; P(E_{\bar{\nu}},E_o^i,Z) \tag{3}$$

Here $Y_n(Z,A,t)$ is the number of beta decays per unit time of the fragment Z,A after the fissioning material has been exposed to neutrons for a time t. For <u>t</u> longer than the fission fragment lifetime the quantity Y_n converges toward the cumulative fission yield. The quantity $b_{n,i}$ is the branching ratio for the beta decay branch with maximal electron energy $E_o^i = Q_n + m_ec^2 - E_{exc}^i$. Finally $P(E_{\bar{\nu}}, E_o^i, Z)$ is normalized Coulomb corrected spectrum shape factor. When the electron spectrum is calculated, the only modification is in the spectrum shape factor P.

Let me describe the calculation in which I have been involved.[2] The necessary experimental information was taken from a standarized set, so called ENDF (Evaluated Nuclear Data File, maintained by the Nuclear Data Center at Brookhaven). However, not all information needed is there. The situation is illustrated in Fig. 1 dealing with Rb nuclei which account for $\sim$ 25% of all antineutrinos at 5-6 MeV. As the mass number increases the nuclei become more unstable. The Q values increase, fission yields typically decrease, and, most importantly, lifetimes dramatically decrease (1000 times in our example). The standard line beta spectroscopy becomes very difficult for lifetimes of a few seconds or less; in our example ^{93}Rb is the heaviest nucleus studied in this way. There is one technique, "on line" or "continuous" beta spectroscopy,[7] which could handle some short lived fission fragments, and the nuclei $^{90-94}$Rb were studied in this way. The shortest lived isotope in Fig. 1, ^{95}Rb, has a completely unknown beta decay scheme. Our file contains five more Rb isotopes, $^{96-100}$Rb, which also have unknown beta decay. Their yields are quickly decreasing and they contribute very little to the neutrino spectrum at 6 MeV. They become important, however, at 9 MeV.

The fission products could be divided into three categories: Those with known decay schemes (k), those with unknown decay schemes (u), and those studied by the continuous beta spectroscopy of Ref. 7 (and by nothing else). The relative contributions to the neutrino spectrum of these groups are shown in Fig. 2. For energies $E_{\bar{\nu}} \leq 2$ MeV, the known nuclei dominate, but these energies are of little interest to neutrino physics. Also, at these energies one has to consider carefully the exposure time dependence (see Fig. 5). On the other hand, for $E_{\bar{\nu}} \geq 6$ MeV the unknown nuclei contribute very significantly and it is crucial to treat their beta decay in a realistic way. An example is shown in Fig. 3. The three sets of branching ratios shown there look different but give very similar electron and antineutrino spectra. The "model", as explained in Ref. 2 assumes that the reduced Gamow-Teller matrix element does not change with excitation. It contains one free parameter, the feeding to states inside the pairing gap, which is the same for a large group of nuclei. This parameter has been adjusted in such a way that the model agrees in a best possible way with the results of Ref. 7.

On the other hand, the model for an unknown nucleus Z, A used in Ref. 3 uses the experience of the more stable nuclei with the same Z but $A-2\underline{n}$. However, beta decays of such nuclei are not the same. In our example ^{89}Rb has 18 beta decay branches, ^{91}Rb has 38 branches, and ^{93}Rb has 65 branches. Another prescription was used by the Soviet group.[8] In the case of ^{93}Rb in Fig. 3, all beta decays would go to states within 1.5 MeV of the ground state. Such a prescription obviously overestimates the high energy part of the neutrino and electron spectra.

The resulting spectra are compared in Fig. 4. The curve AG of Ref. 3 is clearly outside the expected uncertainties of Davis *et al.*[2] (and the spectrum of Ref. 8 is similar to AG). How do we decide which spectrum is correct? The obvious thing to consider is the associated electron spectra. Until recently the situation in that respect was somewhat confusing. The experimental results of Carter *et al.*[9] were closer to the prediction of Davis *et al.*,[2] while those of Tsoulfanidis[10] were closer to the Avignone and Greenwood predictions.[3] Both experimental spectra correspond to short exposure times (a few hours). Remembering that the calculations should be quite reliable at low energies, and taking into account the exposure time dependence shown in Fig. 5, we have to conclude that both experimental spectra[9,10] are too high at low energies. Thus a new measurement was clearly desirable. Such a result is available now. Dickens[11] has reanalyzed some previous Oak Ridge electron measurements and proposed an antineutrino spectrum also shown in Fig. 4. It agrees reasonably well with Davis *et al*; the slight underestimate at higher energies is apparently related to an approximation adopted by Dickens. Of great importance is the precise measurement of the electron spectrum accompanying ^{235}U fission performed recently in Grenoble.[4] This spectrum is very close to the prediction of Davis *et al.*[2] Thus we conclude that the "true" antineutrino spectrum is within the (conservative) uncertainties of Ref. 2.

Now we are in a position to compare the experimental positron spectra of the ccp reaction with expected ones. The most complete data are those from Grenoble at 8.7 m[6] (see H. Kwon's talk at this conference). The results are summarized in Fig. 6. The agreement with the DV curve is good at all energies and no indication of oscillations has been seen.

The older measurement of Nezrick and Reines[5] at 6 m is more difficult to assess. The background of about 15% has not been subtracted in Ref. 5 and its energy dependence is poorly determined. In a plot similar to Fig. 6 with data without background subtraction, one gets again very good agreement with the DV curve for $E_{e^+} \leq 4$ MeV. At higher energies the data are above both theoretical curves. The averaged cross section normalized to the Davis *et al.* prediction is quoted in Ref. 1 as 0.84 ± 0.12 for a 1.8 MeV neutrino threshold and 1.02 ± 0.15 for a 4 MeV neutrino threshold. (I have recalculated the first quantity and I got 0.96 ± 0.13 without background subtraction). Thus, I conclude that at 6 m there are also no substantial deviations from the DV curve and no indications of oscillations.

The available information on the Irvine group[1] measurement at 11.2 m is quite limited. The averaged cross section normalized to Davis *et al.* prediction gives 0.88 ± 0.15 at a 4 MeV neutrino threshold, but only 0.58 ± 0.12 at 6 MeV threshold. This last piece of data indicates lack of neutrinos and possible oscillations even though it comes from the very tail of the positron spectrum. Nevertheless, using this information in conjunction with the deuteron disintegration results, Reines *et al.*[1] conclude that oscillations are present and are characterized by a mass difference $\Delta^2 = 0.85 \pm 0.15$ eV and mixing angle $\sin^2 2\theta = 0.65 \pm 0.15$.

To test the consistency of this finding, I took the midpoint value of Δ^2 and θ and calculated a reduction of $\sim$ 65% in the positron spectrum at $\sim$ 2.0 MeV for 6 m and at $\sim$ 4 MeV for 8.7 m. Such a reduction is not observed and we have to conclude that the three experimental ccp results are not mutually fully consistent. If there are no oscillations, it is necessary to explain the lack of 5 MeV positrons at 11.2 m. On the other hand, if oscillations are present, it is necessary to explain the absence of an appreciable reduction at 6 and 8.7 m.

To these considerations we have to add the deuteron disintegration experiments interpreted as evidence of oscillations at about 3 standard deviation level. The situation is summarized in Fig. 7 from Ref. 6. The results of the two experiments are contradictory at the 68% confidence level, but they just touch at the 90% confidence level.

The fact that the ccd and ccp results at 11.2 m are also not in a perfect agreement, has been recognized already in Ref. 1. Table II summarizes that situation. The measured spectrum there is just the spectrum deduced from the ccp reaction. The corresponding entry for ccd is independent of oscillations and must be compatible with unity. When forming the double ratio ccd/ncd using the measured spectrum, we notice that most of the deviation from unity comes from the numerator and not from the denominator where it should be. Let us note in passing that the ncd entry is compatible with unity for the Davis spectrum and as expected smaller than unity for the Avignone spectrum.

Table II. Summary of results on deuteron disintegration.[1]

Reaction	Spectrum	Avignone[3]	Davis[2]	Measured[1]
ncd		0.77 ± 0.12	1.00 ± 0.15	1.2[a] ± 0.2
ccd		0.30 ± 0.13	0.41 ± 0.18	0.56 ± 0.27

[a] Uncertain because the measured spectrum has not been determined between 2.3 and 4 MeV.

The last half year has been an exciting time for reactor antineutrino physics. The very difficult experiments gave us some very valuable (and very provocative) results. There is obviously no consensus in the physics community on the subjects discussed here and I tried to explain my somewhat subjective point of view. Naturally, we cannot expect a full agreement on matters of such importance before effects of many more standard deviations are observed.

Enlightening discussions with Professor R. P. Feynman are greatly appreciated. This work was supported by DOE Contract DE-AC-03-76-ER00063.

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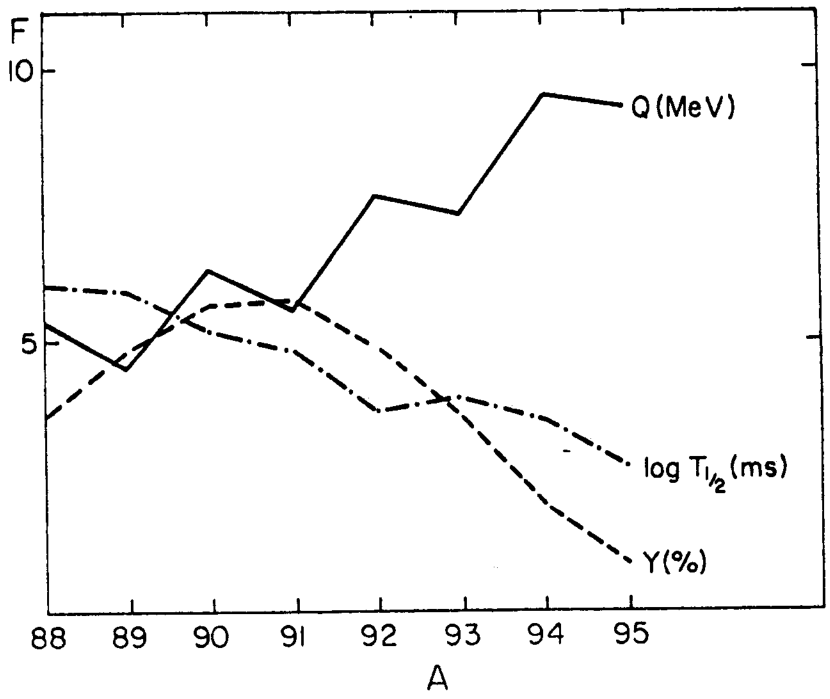

Fig. 1. Fission fragments with Z = 37 (Rb). Full line connects the beta decay Q values, dashed line shows the cumulative yields for ^{235}U fission, and dot-and-dashed line shows the decadic logarithm of the beta decay half-life.

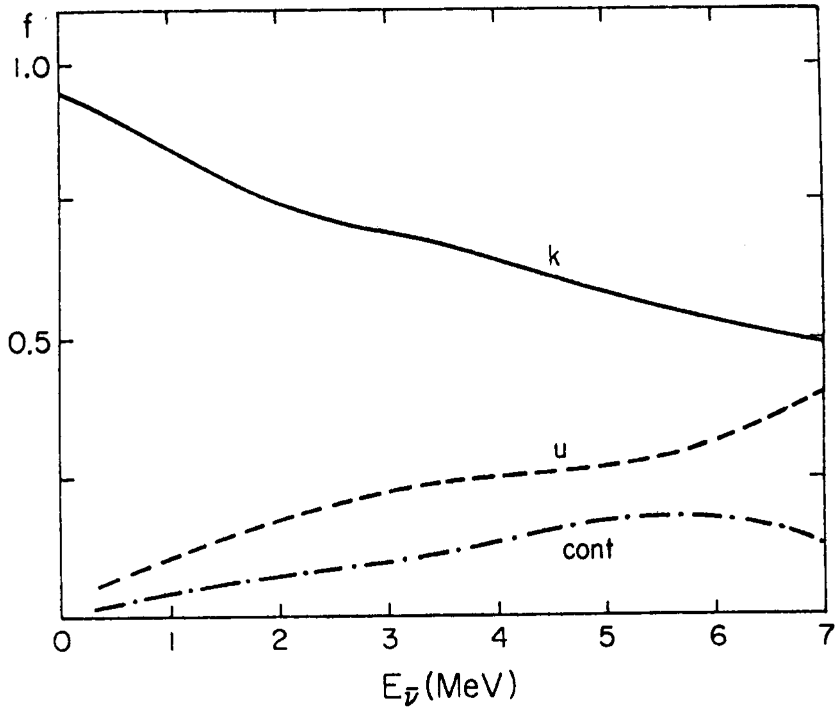

Fig. 2. Contribution of the known (k), unknown (u), and "on line" (cont) nuclei to the neutrino spectrum at various energies.

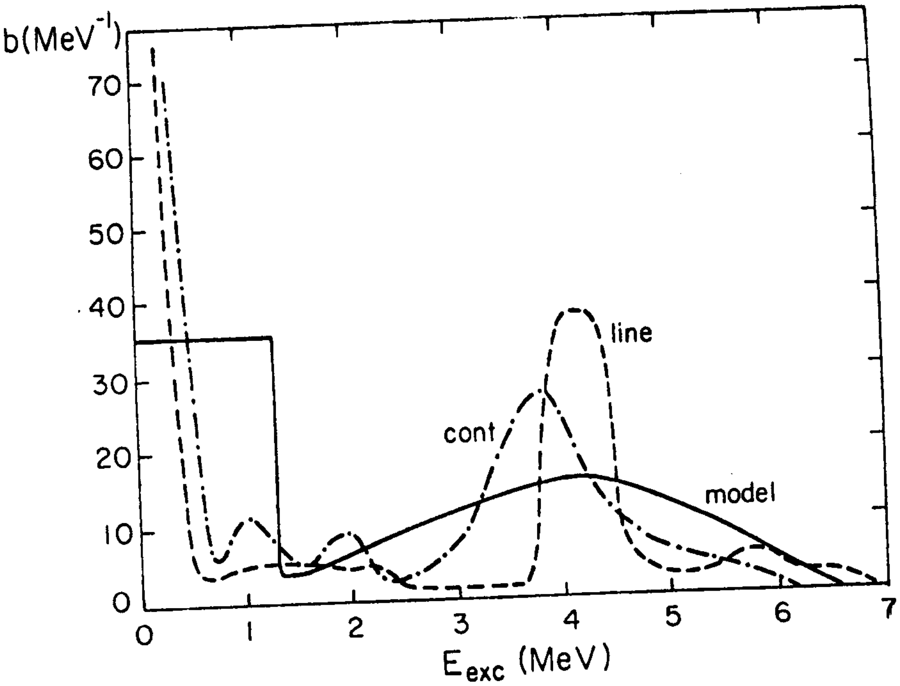

Fig. 3. Beta decay branching ratios for ^{93}Rb. The "model" curve shows the theoretical prescription of Ref. 2. The "line" curve shows branching ratios of the standard beta spectroscopy, the lines are broadened for display here. The "cont" curve are results of Ref. 7.

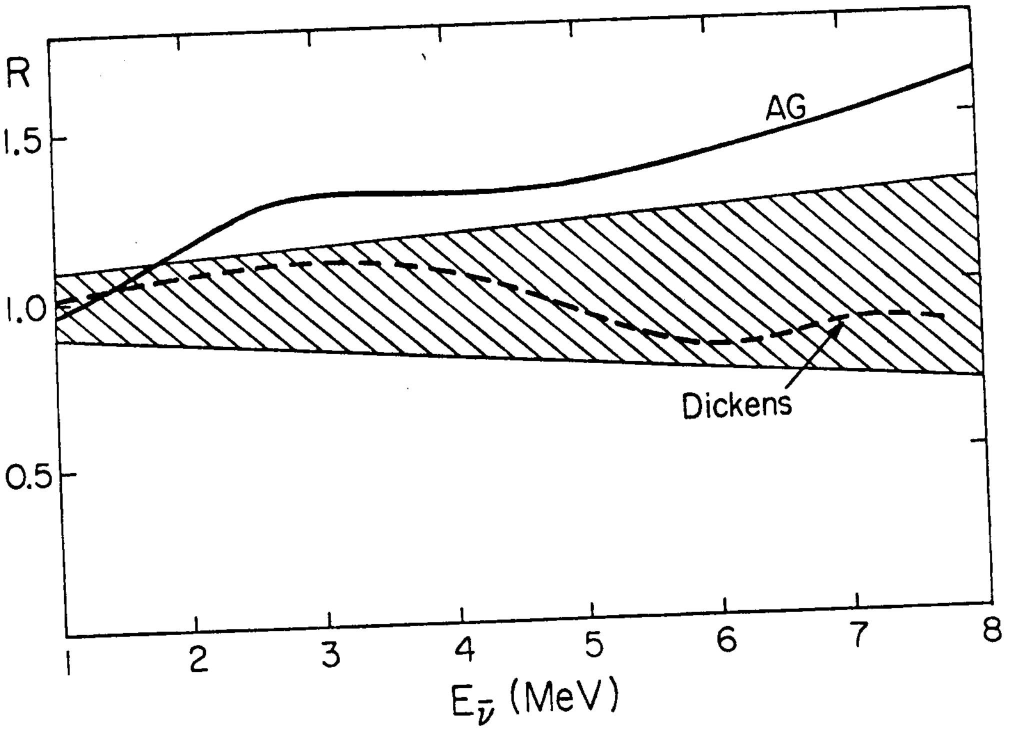

Fig. 4. The spectra of Ref. 3 (AG) and Ref. 11 (Dickens) divided by the spectrum of Ref. 2. The shaded area are uncertainties estimated in Ref. 2.

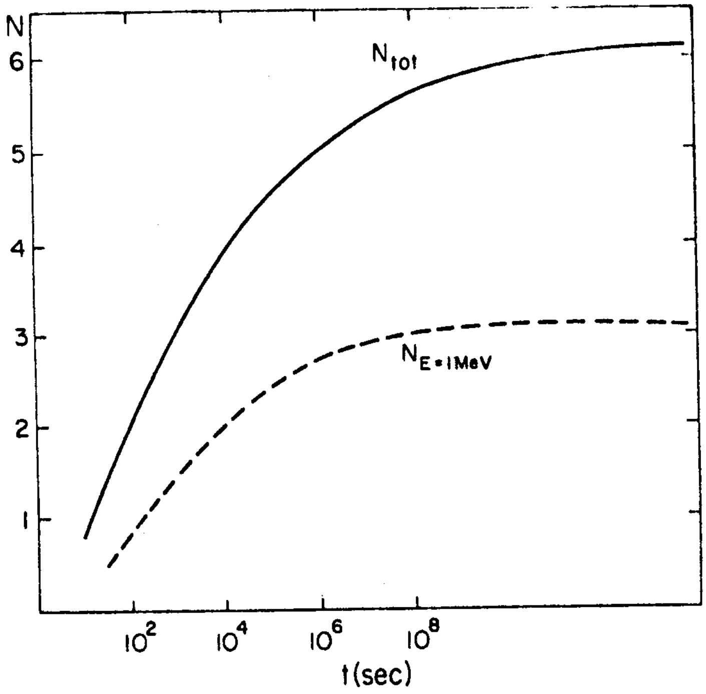

Fig. 5. Exposure time dependence of the total number of electrons per fission (N_{tot}) and of the number of 1 MeV electrons.

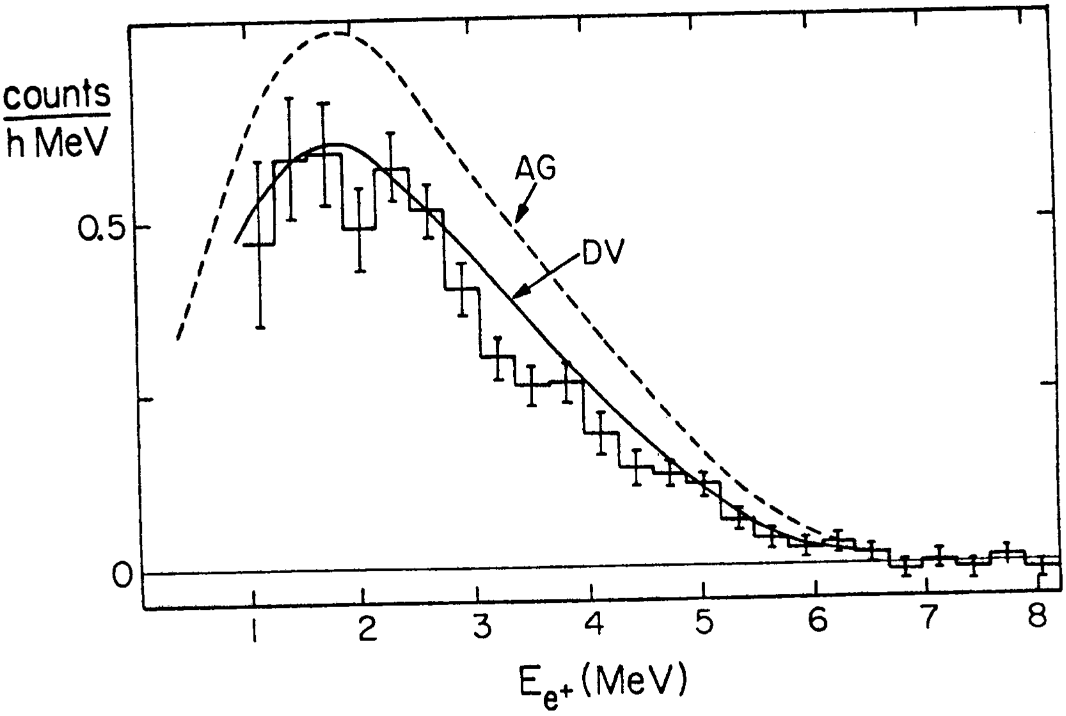

Fig. 6. The experimental positron spectrum at 8.7 m[6]. The theoretical curves are based on Ref. 2 (DV) and Ref. 3 (AG).

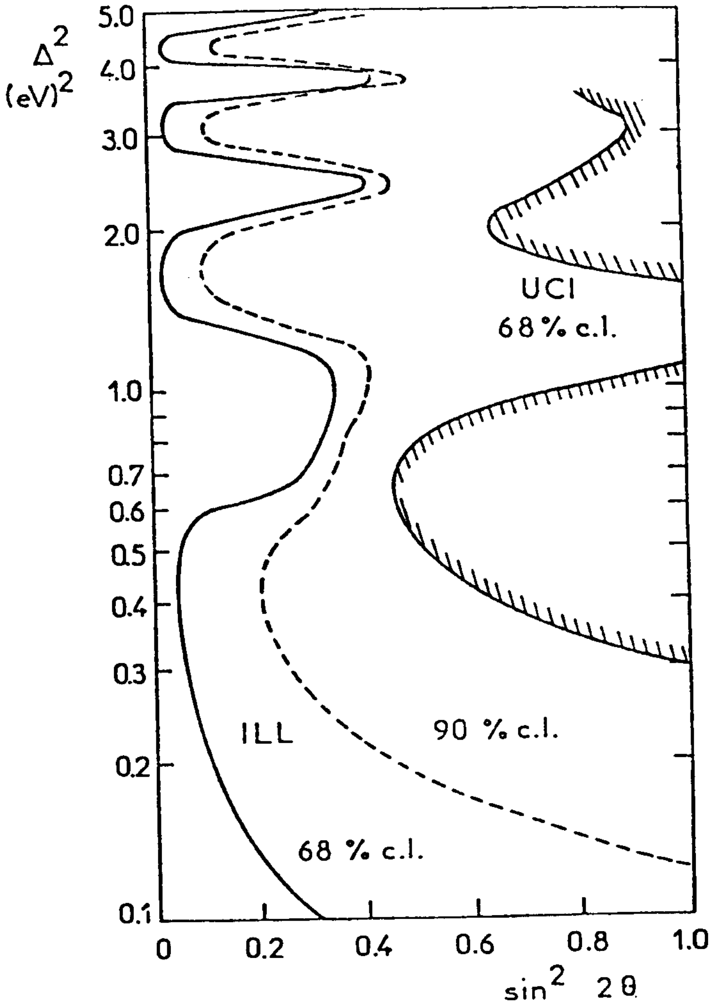

Fig. 7. The limits of the neutrino oscillation parameters. The ILL curves refer to the ccp reaction at 8.7 m^6; the allowed region is to the left of the curves. The UCI curves refer to the ccd/ncd ratio[1]; the allowed region is to the right of the curves.

THE GRENOBLE NEUTRINO OSCILLATION EXPERIMENT

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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 ^{3}He 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