

Neutrino-Induced Upward-going Muons at MACRO

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Upward-going muon events in MACRO allow measurement of the ν_μ flux in the range $E \sim 10$ to 100 GeV. The ratio of total observed to expected events is $0.74 \pm 0.036_{\text{stat}} \pm 0.046_{\text{sys}} \pm 0.13_{\text{theor}}$, which when combined with the observed zenith angle distribution ($-1.0 \leq \cos\theta \leq -0.1$) agrees with the no-oscillation model to no better than 0.1%. The data are in significantly greater agreement with the $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation model, with best-fit parameters of $\sin^2 2\theta \approx 1.0$ and $\Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2/c^4$. The combined probability (total rate and zenith angle distribution) assigned to the data under this best-fit assumption is 17%. These results are consistent with measurements at Superkamiokande and Soudan.

I. INTRODUCTION

Since the atmospheric neutrino “anomaly” was first reported nearly a decade ago, evidence has steadily grown for the possible oscillation explanation of cosmic-ray induced neutrino data [1,2]. The most significant of this has clearly been the Superkamiokande experiment [3], which confirms the effect in upward-going muons, the contained ν_e/ν_μ ratio, and in the zenith angle dependences of both low ($\sim\text{GeV}$) and higher-energy events. The SuperK analysis also indicates a specific range of $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation parameters, $\sin^2 2\theta \approx 1.0$ and $\Delta m^2 \sim 10^{-3}$, which are near the center of MACRO sensitivity [4]. Thus MACRO can address the issue as well, in particular providing another high statistics but non-water-based complement to existing Frejus [5] and Soudan 2 [6] iron calorimeter results.

II. THE MACRO DETECTOR

MACRO, the Monopole, Astrophysics, and Cosmic Ray Observatory [7], is a large-area general-purpose detector located in the Gran Sasso Laboratories of central Italy. MACRO is comprised of six supermodules, each $12 \times 12 \text{ m}^2$ in area and divided into lower (5 m) and upper (“attico,” just over 4 m high) sections. Each contains both limited streamer tube and liquid scintillator detector systems, as well as a passive track-etch detector not utilized in this analysis. The full detector is $77 \times 12 \text{ m}^2$ in area and ≈ 9 m high, with an acceptance for isotropic flux of $\sim 10^4 \text{ m}^2\text{sr}$. The streamer tubes provide ≈ 1 cm spatial and $< 1^\circ$ angular resolution, while the complementary liquid scintillator system has ≈ 500 ps timing resolution and sufficient energy resolution to reject most radioactive background.

Although primarily designed for a GUT magnetic monopole search, MACRO’s excellent tracking ability and large size make it sensitive to other physics as well. In particular this includes cosmic-ray induced (atmospheric) ν_μ ’s, observed via the upward-going muons they produce. In addition MACRO’s great depth (3.15 kmwe minimum overburden) provides excellent shielding from downward-going cosmic ray muons, reducing the backscatter background below the level of other experiments *e.g.* IMB [1] and Baksan [8] without active shields.

III. ANALYSIS

Data presented here were recorded in three separate sets:

1. Mar 89 - Nov 91: 1 Supermodule, no attico (1.38 live-years);
2. Dec 92 - Jun 93: 6 Supermodules, no attico, (0.41 live-years); and
3. Apr 94 - Dec 97: 6 full Supermodules, with attico (2.89 live-years).

Aside from the additional year's data accumulated since our previously published analysis [4], this work also represents an enhanced understanding of detector acceptance and background processes. To begin, neutrino-induced events are fairly straightforward to detect in MACRO, and are selected via the following four cuts:

1. Single throughgoing track, for which scintillator and streamer tube positions agree to ± 70 cm. *Selects throughgoing single muon-like events.*
2. Greater than 200 g/cm^2 material traversed. *Rejects corner clipping and other non-penetrating tracks.*
3. At least two scintillator hits, at least 2 m apart. *Provides adequate pathlength for good time-of-flight (velocity and direction) determination.*
4. Reduced velocity in the range $-1.25 < 1/\beta < -0.75$. *Selects upward-going (negative beta) events consistent with speed-of-light travel.*

The $1/\beta$ distribution of events surviving the first three cuts is presented in Fig. 1.

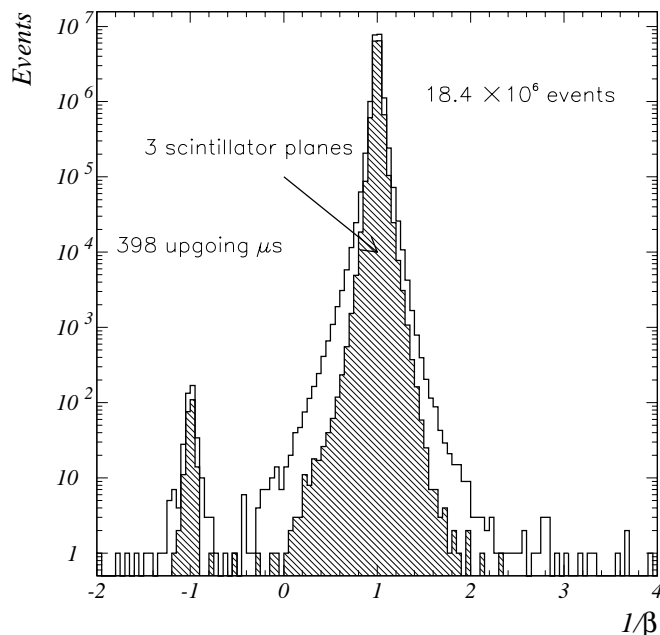


FIG. 1. The $1/\beta$ distribution for a representative subset of events surviving cuts 1-3. Tracks crossing three scintillator planes (shaded) have better timing resolution than, but are not qualitatively different from, the two-plane events. The region $1/\beta > 1$ corresponds to downward-going muons which are ranging out in the detector, while background near the upward-going peak ($1/\beta \approx -1.0$) is due to downward-going muons preceded by radioactive decay.

A total of 479 events survive these cuts, which a Monte Carlo analysis indicates are essentially all the result of ν_μ charged-current interactions. There are, however, three well-understood sources of background;

1. Downward-going muon plus radioactive decay. *When a downward-going muon is preceded by a radioactive decay, event geometry and timing can mimic an upward-going muon (see Fig. 1).* Estimate: 9 ± 5 events.
2. Muon-induced backscatter. *Although MACRO is deeper than the other experiments cited above, the downward-going muon flux can still produce upward-going backscatter (generally pions). Cut 2 above discriminates against such events, but some remain.* Estimate: 8 ± 3 events.
3. “Contained-vertex” events. *Two classes of neutrino candidates, contained vertex and upward-going stopping events, are discussed elsewhere in these proceedings [9] but rejected by this analysis. Nevertheless a small number of the former category remain as background.* Estimate: 11 ± 4 events.

A. The Integrated Flux

The expected number of events is determined using the Bartol neutrino flux [10], the Morfin and Tung parton distributions [11], and Lohmann *et al.* muon energy losses [12], combined with a GEANT-based Monte Carlo simulation of the detector. Including background, 640 events are predicted for the zenith angle range $-1.0 < \theta < -0.1$, while 479 are observed (451 and 612 events, respectively, without background). The ratio is

$$\frac{N_{\text{observed}}}{N_{\text{predicted}}} = 0.74 \pm 0.036_{\text{stat}} \pm 0.046_{\text{sys}} \pm 0.13_{\text{theor.}}$$

The second contribution to the uncertainty represents systematics in detector acceptance, while the third is due to the muon production rate and range, to which the leading contributor is an absolute uncertainty in the cosmic ray flux. As opposed to experiments which detect both ν_e and ν_μ -induced events, and thus form a ratio which reduces such uncertainties, MACRO makes an absolute muon flux measurement. The probability to observe a result as far or farther from unity is

$$P_{\text{total events}} \approx 14\%.$$

Although of limited statistical significance, this result could be interpreted as evidence for neutrino oscillations. In the $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation model, therefore, assuming maximal mixing angle, we determine a best-fit Δm^2 of approximately $2 \times 10^{-3} \text{ eV}^2/c^4$. This value, when input into the Monte Carlo, exactly reproduces the observed number of events.

B. The Zenith Angle Distribution

In addition to the absolute event rate, there is an *a priori* indication that the zenith angle distribution of MACRO events may be of interest to neutrino oscillation hypotheses as well. Assume the standard two-component $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation model, discussed in any introductory text [13]:

$$P(\nu_\mu \rightarrow \nu_\tau) = \sin^2 2\theta \sin^2 \left(\frac{1.27 \Delta m^2 L}{E_\nu} \right), \quad (1)$$

where θ is the mixing angle, L is the neutrino pathlength in km, E_ν is the ν_μ energy in GeV, and Δm^2 is the mass difference in eV^2/c^4 . Since the parent neutrino spectrum ranges from $\sim 1 - 100 \text{ GeV}$ (Fig. 2) while the pathlength varies from a few hundred km just below horizontal to approximately the earth's diameter (12,700+ km) near the anti-vertical, MACRO has greatest sensitivity to mass differences on the order of 10^{-4} to $10^{-1} \text{ eV}^2/c^4$. This is precisely the range indicated by SuperKamiokande and Soudan 2.

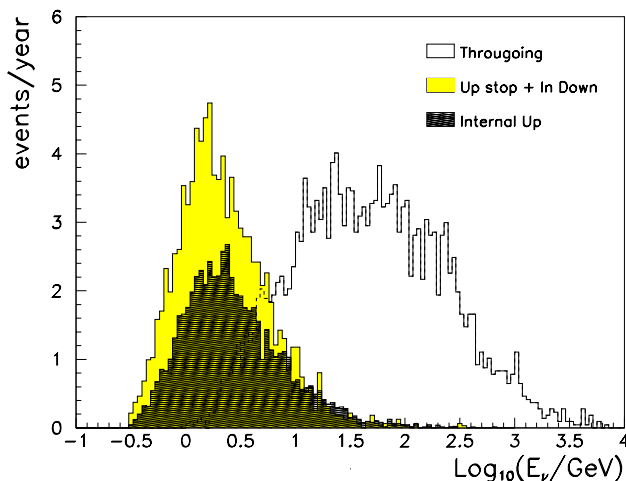


FIG. 2. Interacting neutrino energy distributions in MACRO. Only throughgoing events are considered here, but see [9].

It is clear that the $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation model provides a much better fit to the observed zenith angle distribution (Fig. 3) than the standard model (no oscillation) hypothesis (Fig. 3). The nominal probability assigned to the observed result, based on a combination of the χ^2 of the (normalized) zenith angle distribution and the Poisson probability to see as unusual a total number of events, is

$$P_{\text{combined}} = P_1 P_2 \times (1 - \ln P_1 P_2) \approx 0.1\%,$$

where P_1 and P_2 are the total event number and zenith angle probabilities, respectively. The raw result for the latter is $\chi^2 = 28.1$ for eight degrees of freedom, for which $P_1 \approx 0.1\%$. That is, the 14% probability assigned to the total observed number of events does not significantly affect the combined result.

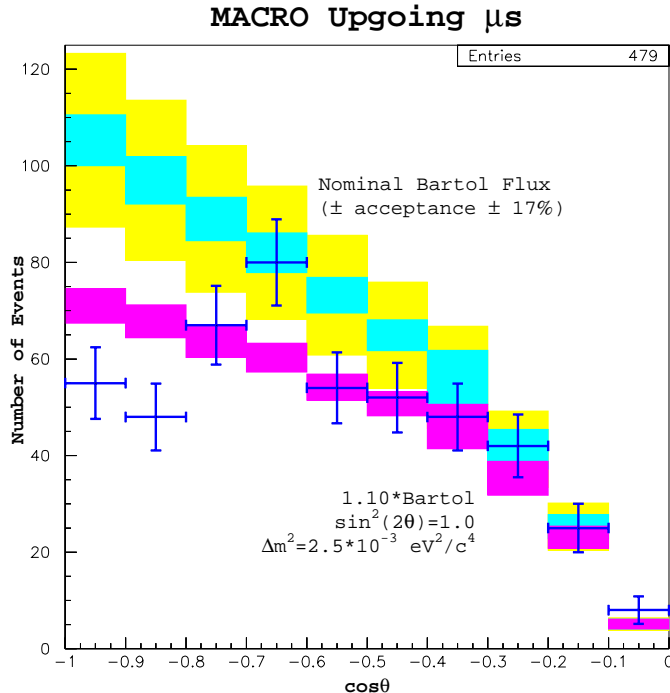


FIG. 3. Zenith angle distribution of MACRO upward-going muon events, with nominal Bartol prediction (net uncertainty $\pm 17\%$). The best-fit $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation parameters ($\sin^2 2\theta \approx 1.0$, $\Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2/c^4$) are also indicated. The last bin ($0.9 < \theta < 1.0$) is not used in this analysis as it includes regions of significantly low overburden.

A best-fit analysis including a possible variation in the total flux yields maximal mixing and the same mass difference obtained in the one-parameter (integrated flux) analysis:

$$\text{Best-fit Parameters:} \quad \sin^2 2\theta \approx 1.0 \quad \text{and} \quad \Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2/c^4,$$

requiring a 10% upward renormalization of the parent neutrino flux. The corresponding probability to observe as unusual or more unusual a result, given the best-fit parameters, is $P_{\text{best-fit}} \approx 17\%$.

This result is dominated by the first four (nearest to anti-vertical) zenith angle bins (Fig. 3). The probability associated with the zenith distribution alone, in fact, is only 5%. Nevertheless possible systematic effects in acceptance (best understood near the antivertical) and rock composition are not large enough to account for this result, nor is there significant variation in the distribution as a function of detector size or the number of scintillator planes hit (Fig. 1). In spite of the relatively low probability assigned to the best-fit zenith angle distribution, therefore, there is no strong evidence for unresolved systematic effects in the distribution.

Two-dimensional contours in mixing parameter space are obtained via the standard unified approach [14], and provided in Fig. 4. The 99% confidence-level region is approximately

$$99\% \text{ Confidence Region:} \quad \sin^2 2\theta > 0.5 \quad \text{and} \quad 2 \times 10^{-4} < \Delta m^2 < 2 \times 10^{-2} \text{ eV}^2/c^4.$$

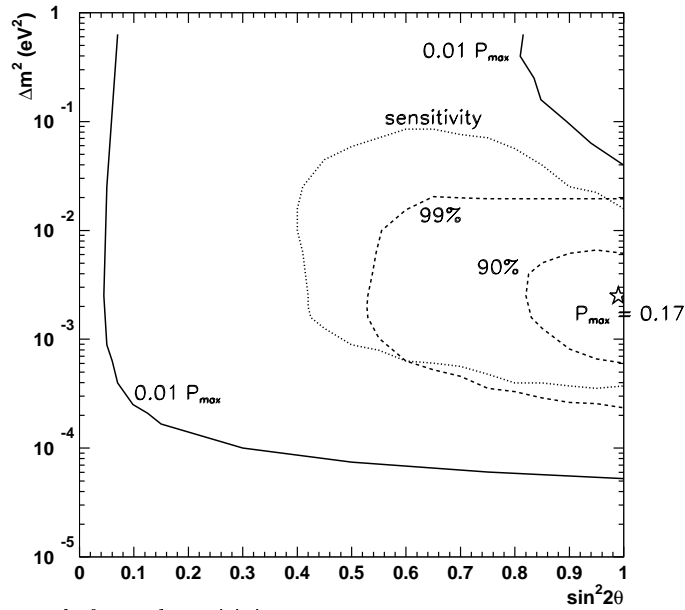


FIG. 4. Unified confidence intervals for and sensitivity to vacuum $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The region $P > 0.01 \times P_{\max}$ is also indicated, with $P_{\max} = 17\%$.

IV. CONCLUSION

The event rate and zenith angle distribution of MACRO upward-going muon data agree poorly with the standard model prediction, to which is assigned a probability of $\approx 0.1\%$. Best-fit $\nu_\mu \leftrightarrow \nu_\tau$ vacuum oscillation parameters $\sin^2 2\theta \approx 1.0$, $\Delta m^2 \approx 2 \times 10^{-3} \text{ eV}^2/c^4$, on the other hand, provide a significantly better fit ($P_{\text{best-fit}} \approx 17\%$). The 99% confidence region $\sin^2 2\theta > 0.5$, $2 \times 10^{-4} < \Delta m^2 < 2 \times 10^{-2} \text{ eV}^2/c^4$ is consistent with both SuperKamiokande [3] and Soudan 2 [6] results, although the latter exhibits moderately higher best-fit Δm^2 .

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