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Atmospheric neutrino flux measurement using upgoing muons

MACRO Collaboration

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Abstract

We report on the first measurement of the flux of upgoing muons resulting from interactions of atmospheric neutrinos in the rock below MACRO. The ratio of the observed to the expected number of events integrated over all nadir angles is $0.73 \pm .09_{\rm stat.} \pm .06_{\rm sys.} \pm .12_{\rm theor.}$. The flux of upgoing muons as a function of nadir angle is presented and compared to Monte Carlo expectations. At the 90% confidence level, the data are consistent with no neutrino oscillations or some possible oscillation hypotheses with the parameters suggested by the Kamiokande contained-event analysis.

Considerable interest has been generated in the last few years in precise measurements of the flux of atmospheric neutrinos due to the apparent anomaly in the ratio of contained muon neutrino to electron neutrino interactions in the Kamiokande [1,2] and IMB [3] detectors. The Frejus and NUSEX detectors have observed the expected number of contained events with smaller statistics [4,5]. The Soudan II collaboration has reported preliminary results which are in agreement with the IMB and Kamiokande observations [6].

The flux of muon neutrinos in the energy region from a few GeV up to hundreds of GeV can be inferred from measurements of upgoing muons in underground detectors. This has been done by the Baksan [7], Kamiokande [8,9], IMB [10,11] and Frejus [12] detectors with no claimed discrepancy with expectations from calculation. Here, we report on the first measurement on these muons with MACRO.

The lower half of the MACRO detector consists of a large rectangular box, 72 m × 12 m × 5 m, with an outer shell of liquid scintillator counters surrounding 10 horizontal layers of plastic streamer tubes. The detector is subdivided into 6 parts which are referred to as supermodules (SM). In addition to the horizontal layers, vertical layers of streamer tubes are included along the sides of the detector. The horizontal streamer tube planes have a 3 cm pitch and are equipped with readout electronics on both the wires and on 3 cm pitch cathode strips. (See [13] for more details of the detector hardware.) In this analysis, muon tracks are reconstructed for events with aligned hits in at least 4 horizontal planes or 2 horizontal planes in coincidence with 3 or more vertical planes. The intrinsic angular resolution for muons which traverse 10 planes of streamer tubes is 0.2°. The area of MACRO used for this analysis is much larger horizontally than vertically with a resulting small number of events near the horizontal.

The data used for this measurement were collected during two different running periods. The first period used one supermodule and lasted from March 1989 until November 1991. During this time (1.4 life-years), 2.3×10^6 muon events were recorded. The second running period, from December 1992 until June 1993,

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used 6 supermodules (0.42 life-years) during which 3×10^6 muon events were recorded.

The direction that muons travel through MACRO is determined by streamer tube tracks and by the time-of-flight between two different layers of scintillation counters. The time resolution for muons in a scintillator box is about 750 ps for the 1 SM data and 500 ps for the 6 SM data, the improvement being the result of electronics upgrades. Timing is used to calculate the β for each muon with the convention that downgoing muons will be expected to have β's near +1 while upgoing muons will be expected to have β's near −1.

The timing information in a given scintillator tank can be incorrect in some cases: when a radioactive decay occurs in a tank nearly coincident with the passage of a muon; when muons stop in the detector; when multiple muons are in a single event; or when muons are accompanied by large electromagnetic showers. These effects tend to produce non-Gaussian tails in the $1/\beta$ distribution which must be removed to attain a clear peak of upgoing muons near $1/\beta = -1$. A 3 m minimum pathlength requirement has been imposed to ensure that the time of flight is significantly larger than the time resolution of the scintillator system. Consistency in position measurements using streamer tubes and scintillator timing has also been imposed to help eliminate background. Since the readout electronics for MACRO is symmetric for upgoing and downgoing muons, downgoing muons have been used to check the efficiency of these cuts. The measured efficiency is 94% for downgoing muons.

Fig. 1 shows the $1/\beta$ distribution for the combined 6 SM and 1 SM data sets (after analysis cuts). A clear peak of events is visible centered on $1/\beta = -1$. Events with $-1.25 < 1/\beta < -.75$ are defined to be upgoing muons. This range corresponds to a 4 σ cut for the 6 SM data and a 3 σ cut for the 1 SM data assuming a Gaussian distribution for $1/\beta$ for the upgoing muons. There are 51 events which satisfy this definition for the 6 supermodule data and 26 events for the 1 supermodule data.

All events which have $1/\beta < 0$ but lie outside of the defined signal region have been studied carefully to determine whether they have characteristics of background events or may be poorly reconstructed upgoing muons. Two events appear that they could possibly be the latter. We include a systematic error in our acceptance for upgoing muons based on these

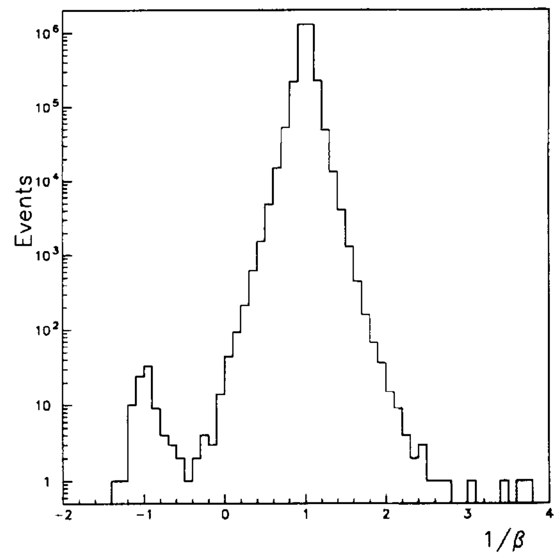

Fig. 1. Distribution of $1/\beta$ after analysis cuts for the combined 6 supermodule and 1 supermodule data sets.

two events and do not include them in determining the background. The amount of background is determined by making a Gaussian fit to the signal region around $1/\beta = -1$ together with a linear fit for the region of $1/\beta < -0.2$. From this, we estimate that there are 3 ± 2 background events which are included in the upgoing muon sample. This background is subtracted in the final analysis.

The Monte Carlo simulation is done in three steps. First, a flux of muons at the detector from atmospheric neutrino interactions is calculated. Second, the acceptance for these muons is calculated for the detector geometry in a particular running period. Finally, an efficiency correction is applied to the expected number of events based on electronic and reconstruction efficiencies which have been explicitly measured using downgoing muons.

Four different calculations of the atmospheric neutrino flux have been used: that from Bartol [14], the one from Butkevich et al. [15], that of Mitsui et al. [16] and another from Volkova [17]. The flux of upgoing muons based on the Bartol and Butkevich neutrino fluxes are about the same while the muon flux based on the Volkova and Mitsui flux is lower by about 10% than the first two. The authors of the Bartol flux have estimated the systematic uncertainty by varying the input parameters (primary cosmic ray flux, interaction cross-sections, secondary pion and kaon spectra, etc.). They estimate the systematic error on the flux of upward-going muons with energy greater than 3 GeV at the detector due to uncertainties in the neutrino flux to be ±13% if constraints from atmospheric muon measurements are taken into account [18]. (Without this constraint from the atmospheric muon measurements the uncertainty is about 20% [19].) Butkevich et al. have estimated the systematic uncertainty from this source to be ±10%. For a discussion of the sources of systematic uncertainty in the flux see [20].

The cross-sections for neutrino interactions have been calculated using the Morfin and Tung parton distributions set B1-DIS [21]. A recent discussion of low-energy cross-sections suggests that the through-going muon flux may be increased by a few percent depending on the treatment of quasi-elastic, resonant pion production and scaling violations arising from QCD effects [22]. However, the magnitude and even the sign of this effect depend on neutrino cross-sections in a region where the experimental data are not very clear. Here, we use the simple prescription of calculating the cross-section but include a systematic error of ±9% on the expected flux of through-going muons in MACRO due to all uncertainties in the cross-section. The propagation of muons to the detector has been done using the energy loss calculation of Lohmann et al. [23] using standard rock. The systematic uncertainty on the expected flux of through-going muons in MACRO due to uncertainties in the energy loss and material of the rock below the detector is ±5%. The total systematic uncertainty on the expected flux of muons at the detector is given by adding the errors from the neutrino flux, cross-section and muon propagation in quadrature. The resulting systematic uncertainty is ±17%.

The detector has been simulated using both a GEANT [24] based Monte Carlo program and a simpler geometric model of the detector including all relevant dimensions of scintillator boxes and streamer tubes. The simulated events are processed through the same analysis chain as the data. Comparison between several different calculations of the acceptance of the detector shows an uncertainty in the acceptance of 4% for muon trajectories with cos(zenith) < −0.4 (5.8% averaged over all zenith angles). The Downgoing muons have been studied to understand the effect of the various background removal cuts on the data. These cuts result in additional inefficiencies for real

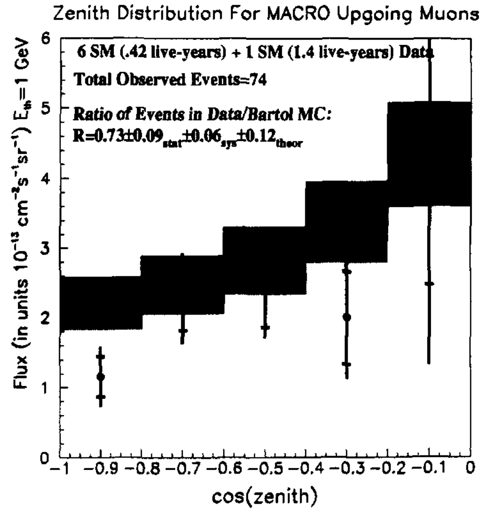

Fig. 2. Distribution of cos(zenith) for the upgoing muon flux with energy greater than 1 GeV for the combined data from the 6 supermodule and 1 supermodule running. The extensions to the statistical error bars are the point-by-point estimates of the systematic error. The Monte Carlo expectation using the Bartol flux is shown in the shaded regions with a ±17% systematic error range.

events which are not simulated by the Monte Carlo. However, the (large) sample of downgoing muon events has been used to directly measure the efficiency that these cuts should have on upgoing muons.

Fig. 2 shows the zenith angle distribution of the measured flux of upgoing muons with energy greater than 1 GeV for the combined 6 SM and 1 SM data sets compared to the Monte Carlo expectation using the Bartol neutrino flux. The distributions for the two data sets are mutually consistent within the statistical errors. The error bars on the data show the statistical errors with an extension for the systematic error calculated separately for each point. The range for the Monte Carlo expectation reflects the ±17% systematic uncertainty in that prediction. A background subtraction of 3 events has been applied to the data on a bin-by-bin basis according to the observed angular distribution of background events that are not in the $1/\beta = -1$ peak (which resembles that for downgoing muons).

The systematic error bars on the data represent the combined systematic uncertainties of the detector acceptance or efficiency. By studying the acceptance and efficiency for downgoing muons with comparisons between the streamer tube and scintillator data and different scintillator triggers, the systematic uncertainty has been reduced to a relatively small value. The remaining sources of systematic error include the uncertainties in: the geometric acceptance averaged over all zenith angles ($\pm 5.8\%$ for all bins or $\pm 4\%$ for the first three bins); uncorrected electronic trigger inefficiencies ($\pm 1\%$); the efficiency of cuts on showering events ($\pm 1\%$); the acceptance of events with interaction vertices very near the detector ($\pm 3\%$); the 2 events mentioned earlier ($\pm 3\%$); correlated inefficiencies between the streamer tube system and scintillator system ($\pm 2\%$); and the background subtraction ($\pm 3\%$). The systematic uncertainty on the acceptance for the larger zenith angle bins is higher due to detector geometry effects and smaller statistics from downgoing muons. The sum of all systematic errors on the acceptance added in quadrature is $\pm 8.2\%$. It is expected that most of the systematic errors will be reduced in future running of MACRO due to inclusion of the top half of the detector and improved statistics.

The total number of upgoing muons observed (after background subtraction) was 74 with an estimated systematic uncertainy in the acceptance of 6 events. The expected number of events is $101 \pm 17_{\text{theor.}}$, using the Bartol neutrino flux. The ratio of the observed number of events to the expectation is $0.73 \pm 0.09_{\text{stat.}} \pm 0.06_{\text{sys.}} \pm 0.12_{\text{theor.}}$. The measured flux is somewhat less than the prediction based on the Bartol flux of neutrinos. Most of this deficit lies in the bin of $-1.0 < \cos\theta < -0.8$ but most bins yield a slightly lower flux than expected. The probability that the observed number of events could differ from the expectation by this amount or more is determined to be 22% by adding all errors in quadrature and assuming a Gaussian distribution of errors. However, it is the error on the Monte Carlo prediction of the upgoing muon flux that dominates. The probability that the observed number of events could differ from the expectation by at least the amount observed, given that the central value of the Monte Carlo predicted upgoing muon flux is correct, is 5%. The systematic uncertainty in the Monte Carlo prediction is dominated by the uncertainty in the calculation of normalization of the flux of the atmospheric neutrinos. Taking into account only the other uncertainties in the upgoing muon flux (cross-section, rock and muon energy loss), the probability that the observed number of events could differ from the expectation by at least the amount observed is 13%, given that the central value of the Bartol neutrino flux is correct.

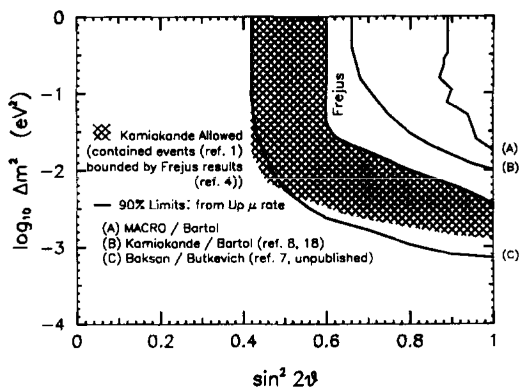

Fig. 3. The 90% confidence level contour for MACRO data for exclusion of large mixing parameters. No lower limit for parameters is shown since the data are consistent with no mixing at the 90% confidence level. Also shown in the plot are previous limits which are calculated under similar assumptions to those used for the MACRO limit along with the region allowed for parameters based on the Kamiokande analysis for contained events. (Note that the limit reported by Baksan using the Butkevich flux assumes the systematic error on the flux is $\pm 10\%$. A limit also exists for IMB data but using different assumptions on the flux [10].)

The observed flux is compared to hypotheses assuming attenuation of the predicted flux by neutrino oscillations between ν_μ and some other ν that is undetected (assuming only two flavors mix). Fig. 3 shows a 90% confidence level contour on an upper limit for Δm^2 and $\sin^2 2\theta$ for our data and other experiments. Although the MACRO data are consistent (at the 90% confidence level) with the hypothesis that no oscillations occur, the region in parameter space which is most consistent with the MACRO data corresponds to the region of parameter space suggested by the contained-event analysis of Kamiokande. Because our data lie below the predicted flux, only a very small region of large mixing parameters is excluded.

In conclusion, we have made a first measurement of the flux of upgoing muons with energies greater than 1 GeV with the MACRO detector. The ratio of the total number of events observed to the number predicted using the Bartol flux is $0.73 \pm 0.09_{\text{stat.}} \pm 0.06_{\text{sys.}} \pm 0.12_{\text{theor.}}$. The probability that the observed number of events could differ from the expectation is 22% assuming the Bartol flux and taking into account all of the systematic and theoretical uncertainty. The results for the Butkevich flux are similar. Although this deficit gives good consistency with neutrino oscillation hypotheses suggested by contained-event analyses, it is also consistent with a no-oscillation hypothesis at the 90% confidence level.

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