August 10, 2000

DfP 2000
California Institute of Technology
Douglas Michael

Search for point sources of neutrinos

- Neutrino induced events in MACRO
- Upgoing Muon data in MACRO
- Constraints on Oscillation Parameters and Flavor
- Participation

In MACRO

Neutrino-induced Upgoing Muons
The Earth and Atmospheric Neutrinos
those for $\nu_e$ and $\bar{\nu}_e$ are relatively suppressed compared to oscillations involving the core of the Earth. Due to matter effects in the Earth's dense layers (Earth's interior), the shape of the angular distribution is modified for $\nu_e$- and $\bar{\nu}_e$-oscillations.

For "standard" solar neutrinos $\sin^2 2\theta = 1$.

Expected effect of oscillations on macro-upward muons.
- 1.3 > |p_T| > 0.7 for "upgoing"
  - resulting in >3% of events cut
  - equipment and data quality cuts
- Astrophys. Phys. 6 (1969) 107
  - m/s produced by muons
  - from m's produced by muons
crossed to reduce the background
- (cm^2) of absorber
  - 2 m (~2000 cm^2) of absorber
downgoing showers
- coincidence radiocactivity and
  - removes events with near
- track and scintillator counter hits
- agreement between streamer
- Event Selection Criteria:

<table>
<thead>
<tr>
<th>Date</th>
<th>Event Type</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>00, Mar 96</td>
<td>691</td>
<td>1996</td>
</tr>
<tr>
<td>51, Apr 94</td>
<td>51</td>
<td>1994</td>
</tr>
<tr>
<td>0, Jun 93</td>
<td>6</td>
<td>1993</td>
</tr>
<tr>
<td>16, Nov 92</td>
<td>16</td>
<td>1992</td>
</tr>
<tr>
<td>68, Mar 91</td>
<td>68</td>
<td>1991</td>
</tr>
</tbody>
</table>

The Upgoing Muon Data Set
Which passed through MACRO

An upgoing charged particle

Upgoing Planes From Downgoing Muons
\[ \sin^2 2\theta = 1.0 \]
\[ \Delta m^2 = 0.0025 \text{ eV}^2 \]
\[ \rho = 26\% \]
\[ \chi^2 = 11.2/8 \text{ d.o.f.} \]
\[ p = 0.9\% \]
\[ \text{No osc.: } \chi^2 = 24.3/9 \text{ d.o.f.} \]

Normalized fit results (shape):
Shape uncertainty = 5\%

\[ R = 0.73 \]

689 ± 17 events observed
723 neutrino-induced muons

Upward-going muon flux \(10^{-3} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \)

UpcomingMuon Results from MACRO
No oscillations: 0.4% 
With vacuum oscillations: 57% 

\( \sin^2(2\theta) \)

Combined Probability:

MACRO March 2000 Data

90% Confidence Level

\( \Delta m^2 \) (eV^2)

10^0

10^1

10^2

10^3

10^4

Number of Events

Angular Distribution

Angular Distribution

Combination

From the combination: 57% 
Peak probability from the angular distribution: 26% 
With maximal mixing

Probabilities for \( \Delta m^2 \)

\( \nu_\mu - \nu_\tau \) oscillations

Vacuum Oscillation Parameters from MACRO
$\nu - \nu^e$ Oscillations

Matter Effects on Macro Upgoing Muons
\[ \sin^2(2\theta) \]

Angular Distribution + Normalization

\[ \Delta m^2 (eV^2) \]

Number of Events

Sterile Oscillations

\[ \nu^\mu - \Delta \nu^\mu \]

Material Effects on Macro Utoping Muons
Total systematic uncertainty ~ 7% .

Systematic uncertainty in MACRO acceptance ~ 5% .

Flux uncertainty ~ 3% from K/τ ratio and uncertainty on spectrum .

Errors on the ratio:

\[ \frac{p_{\text{best}}}{p_{\text{Tau}}} \]

\[ m_r^2 (eV^2) \]

Optimized for \( A m^2 = 0.0025 eV^2 \)

\[ \frac{p_{\text{best}}}{p_{\text{Tau}}} \]

(5% systematic in each bin)

\[ m_r^2 (eV^2) \]

This is due to the fact that oscillations to \( \nu_e \) get "washed out" over decades of energy comparison of oscillations to \( \nu_e \) or \( \nu_x \) (Lipari and Lussutri, Phys Rev D 57 (1998)).

Using the ratio of upgoing muons near the vertical provides extra discrimination for...
Map of the sky with macro neutrinos

Consistent with coming all

from atmospheric neutrinos

Currently ~1100 events

in the "astronomy" sample

-90

0

+90

40

24h
Limits on the flux of neutrinos from astrophysical point sources

<table>
<thead>
<tr>
<th>Source</th>
<th>θ (degrees)</th>
<th>Eν (GeV)</th>
<th>Flux Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>90% CL Limits</td>
<td>90% CL Limits</td>
<td>Previous V-Flux</td>
<td>90% CL Limits</td>
</tr>
</tbody>
</table>

- **Cyg X-3**: 90.3 GeV
- **MKV 501**: 38.4 GeV
- **MRK 421**: 35.4 GeV
- **HER X-1**: 38.7 GeV
- **Cen X-4**: 18.3 GeV
- **SS 433**: 5.7 GeV
- **Aquarius**: 1.0 GeV
- **Sco X-1**: 13.6 GeV
- **Kepler 604**: 21.5 GeV
- **Gal Cen**: 28.9 GeV
- **Vel x 1**: 40.5 GeV
- **SN 1006**: 41.7 GeV
- **Vel x 1**: 4.5 GeV
- **G IX 39**: 48.8 GeV
- **SN 1987A**: 69.3 GeV
- **LMC X-2**: 72.0 GeV
- **SMC X-I**: 73.5 GeV

From the sun's center or the earth or the galactic center, the inclusion from the observed, no clear sources have been observed. Earth and sun.

WIMP models for the supersymmetric sources and point limits set on point.
MACRO running finishes in December 2000. 9 additional months of data.

- sterile (best) = 15 (standard), 70 (optimized) for ratio of vertical/horizontal
  $p^{2.5} = \frac{p_{sterile}}{p_{\text{shape alone}}} = \frac{4}{4}$ from shape alone

The data disfavor a "standard" sterile neutrino:

- $p = 0.4\%$ for combination of shape and absolute flux
- $p = 0.9\%$ on shape alone

- $p = 26\%$ for shape alone

A low probability is obtained for no oscillations:

- Best parameters: $\sin^2 2\theta = 0.1, \rho = 0.7, \Delta m^2 = 0.002-0.007 \text{ eV}^2$
  $p = 50\%$ for combination of shape and absolute flux

- $p = 26\%$ for shape alone

The current data provide a good fit for $\nu^1 - \nu^2$ oscillations:

- Neither the amplitudes of the detector have changed for < 3 years

- Only statistics indicate smoother with time

The angular distribution of MACRO upgoing muons has

Conclusions