Measurement of the Cosmic Ray Induced Muon Flux through the Atmosphere using IMAX

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Abstract

Measurements of both the positive and negative components of the atmospheric muon flux have been performed using the Isotope Matter Antimatter eXperiment (IMAX). Preliminary results based on a partial data set and an early version of the analysis routines have been reported previously (Krizmanic et al., 1995). The experiment was flown from Lynn Lake, Manitoba, Canada (56° latitude, geomagnetic cutoff ≈ 100 MV) on July 16-17, 1992 and experienced an unusually long, 7+ hour ascent from approximately 0.3 km to 36 km above sea level. The unique capabilities of the IMAX instrument yielded muon samples which are uncontaminated from backgrounds due to nuclei, pions, and electrons. Measurements of the muon flux and charge ratio in the momentum intervals 0.22 - 0.32, 0.37 - 0.42, and 0.42 - 0.47 GeV/c at the top of instrument (TOI) as a function of atmospheric depth are presented with a comparison to previous measurements and muon flux predictions.

1 Introduction:

Balloon-borne astroparticle physics experiments offer a valuable and unique resource in their ability to measure particle flux through the atmosphere. In particular, the measurement of the secondary muon flux as a function of atmospheric depth can be employed to indirectly measure the atmospheric neutrino flux (Perkins, 1984; Gaisser, 1990) which is needed to predict neutrino interaction rates in deep underground experiments. Moreover, analysis (Perkins, 1993a) of the balloon-borne, muon flux measurements were critical in determining that the source of the atmospheric neutrino anomaly was due to a ν_μ deficit as opposed to a ν_e excess (Perkins, 1993b; Barish, 1995). The results of the Super-Kamiokande experiment (Fukuda et al., 1998) have strongly solidified the measurement of the atmospheric neutrino anomaly and support the hypothesis of neutrino oscillations as the cause of the anomaly. The absolute neutrino flavor flux must be known to sufficient accuracy to determine neutrino oscillation parameters. Presently, the neutrino fluxes are predicted to an accuracy of approximately 25% (Fukuda et al., 1998). Thus, accurate measurements of the atmospheric muon flux can be used to reduce the uncertainty in neutrino flux predictions.

2 The IMAX Apparatus:

The IMAX apparatus (Mitchell et al., 1996) consisted of a charged particle, magnet rigidity spectrometer (MDR ≈ 200 GV for $Z = 1$), a time-of-flight (TOF) system, two aerogel Cherenkov counters, a Teflon Cherenkov counter, and two dE/dx scintillator counters. A single coil superconducting magnet provided a magnetic field in the tracking volume varying from 0.1 - 2.1 Tesla. Charged particle tracking was performed via two drift chambers and three sets of MWPC's which were located above, below, and in between the drift chambers. This combination yielded 20 planes of measurements in the bending plane and 12 in the non-bending plane. The two aerogel Cherenkov counters ($n = 1.043$, with 11 and 13 photo-electron respective responses for $\beta = 1$) yielded threshold momenta (inside the instrument) of 0.35 GeV/c for muons, 0.47 GeV/c for pions, and 3.2 GeV/c for protons. The TOF system ($\sigma_t = 122$ psec for $\beta,\ Z = 1$) was formed by two planes of scintillators separated by 2.5 meters. Each plane of TOF scintillator was comprised of three individual paddles. The event trigger was formed by a four-fold coincidence between the PMT's on the upper and lower TOF paddles. The nominal geometry factor of IMAX was 144 cm^2-sr at rigidities larger than 1 GeV/c and 115 - 120 (60 - 110) cm^2-sr for rigidities between of 0.35 - 0.4 (0.2 - 0.3) GV/c.

3 Event Selection Criteria and Analysis:

The first stage of the data reduction was to accurately identify clean, $Z = 1$ tracks in the active elements of the instrument. This was then followed by criteria which rejected any non-muonic backgrounds in the momentum range of interest. In the momentum range 0.22 - 0.32 GeV/c (TOI), the time resolution of the TOF system combined with the momentum measurement of the tracking system allowed for the accurate mass reconstruction of the traversing particle. The requirement that both the aerogel Cherenkov counters be under threshold removed any electron background. A selection of events with $\beta > 0.5$ eliminates any protons and heavier nuclei from the data sample. Any effects due to ridigity measurement errors are negligible. These selection criteria yield an uncontaminated sample of muons and pions.

The resolutions of the TOF and tracking systems in the momentum range of 0.22 - 0.32 GeV/c (TOI) allow for the separation of muons and pions via the reconstructed mass. Although atmospheric pions produced by cosmic ray primaries should represent a small ($\approx$ 1%) fraction, a significant amount of pions were identified. This pion background is associated with the interactions of cosmic ray primaries with the support structure around the top of the instrument. Pions were removed by requiring the reconstructed mass of a particle in the momentum range of 0.22 - 0.32 GeV/c (TOI) to be less than $m_\mu + 2\sigma_{m_\mu}$ *and* less than $m_\pi - \sigma_{m_\pi}$. The first requirement defines the selection for virtually the entire momentum range. An estimate of any pion background is obtained by looking at the distribution defined by the reflection of these muon mass selectors about the pion mass, i.e. examining the other side of the reconstructed pion mass distribution. This estimation yields almost no pion contamination in the ascent data and a 5.9% pion contamination in the float data in this momentum range. Any identified pion events are subtracted from the data sample.

In the momentum range 0.37 - 0.47 GeV/c (TOI), only muons and electrons are above the aerogel Cherenkov threshold. This momentum region is divided into two equal momentum bins to accurately take into account the increasing acceptance as a function of momentum. Muons are then selected by restricting the normalized ($C_{Yield} = 1,$ for $\beta = 1$) aerogel light yield via $0.08 < C_{Yield} \leq 0.49$ for $0.37 \leq p < 0.42$ GeV/c (TOI) and $0.08 < C_{Yield} \leq 0.7$ for $0.42 \leq p < 0.47$ GeV/c (TOI). A velocity requirement of $\beta > 0.8$ removes any nuclei from the data sample. Fully-radiating electrons and any sub-threshold particles producing δ-rays are rejected by restricting the accepted aerogel light yields. An examination of events below the aerogel Cherenkov threshold indicate a $<$ 3% probability of being accepted into the data sample. An analysis of the fully-radiating, $\beta \approx 1$ data leads to a contamination probability of $<$0.25% ($<$2.6%) for the momentum range 0.37 - 0.42 GeV/c (TOI) (0.42 - 0.47 GeV/c (TOI)). The absence of any background was verified by analyses which used more restrictive selection on the aerogel Cherenkov signals. Very similar muon spectra were obtained albeit with reduced statistics. The probability for pions to be accepted due to rigidity measurement errors is $<$0.05%.

The efficiency for accepting muons was determined by comparing the IMAX μ^+ and μ^- flux at 0.3 km above sea level in each momentum range of interest to previous results (De Pascale et al., 1993). This methodology yields IMAX μ^+ acceptances of 0.2126 $\pm$ 0.0416 for $0.22 \leq p < 0.32$ GeV/c (TOI), 0.1545 $\pm$ 0.0233 for $0.37 \leq p < 0.42$ GeV/c (TOI), and 0.2927 $\pm$ 0.0289 for $0.42 \leq p < 0.47$ GeV/c (TOI), and μ^- acceptances of 0.2300 $\pm$ 0.0471 for $0.22 \leq p < 0.32$ GeV/c (TOI), 0.1580 $\pm$ 0.0238 for $0.37 \leq p < 0.42$ GeV/c (TOI), and 0.2749 $\pm$ 0.0300 for $0.42 \leq p < 0.47$ GeV/c (TOI). The decrease in the acceptance from the first to second momentum bin is caused by the Cherenkov selection requirement being near the aerogel threshold. These values of acceptances agree with that obtained via examination of individual detector sub-systems.

Using the flight times, livetimes (nominally 75%), muon acceptances, and the IMAX geometry factors, the measured positive and negative muon event rates were each converted to flux as a function of atmospheric depth. The μ^- and μ^+ flux and μ^+/μ^- charge ratio for each of the momentum bins is presented in Figure 1. Also presented in the figure are the predicted muon flux and ratios (Stanev, 1999) from the Bartol atmospheric Monte Carlo (Barr, Gaisser, & Stanev, 1989) which used the latest IMAX primary, cosmic ray spectra measurements (Menn, at al., 1999) as input. Also superimposed on the μ^- flux figures are the results from the lowest momentum bins reported from two flights of the MASS experiment (Bellotti et al., 1996; 1999).

4 Discussion:

From the IMAX results presented in Figure 1, both the μ^+ and μ^- fluxes increase as the muon momentum increases in the range presented in this analysis. The IMAX μ^- flux in the lowest momentum range agrees with that reported by the MASS collaboration (Bellotti et al., 1993; 1999). However, the IMAX results increase systematically over the MASS results as the IMAX momentum increases. This could be due to the effects of the larger momentum bins used in the MASS analysis, the higher geomagnetic cut-off of the MASS91 flight (Ft. Sumner, NM), and the fact that the MASS89 flight occurred during a Forbush decrease.

Starting with μ^+/μ^- ratios, the IMAX measurements and the the predictions of the Bartol Monte Carlo are in good agreement. A comparison of the muon flux measurements to the predictions indicate good agreement at the smallest atmospheric grammage although the highest momentum measurement is approximately 30% higher than the prediction. The lowest momentum data exhibit an interesting feature in that the Bartol muon flux is over-predicted as the atmospheric grammage is increased. This agreement between the measurements and predictions is recovered at the deepest grammage point at ground level. However, the level of disagreement between the measurements and predictions for the trans-atmospheric grammages decreases as the muon momentum increases. It is thought (Stanev, 1999; Coutu 1999) that the source of this disagreement is due to the 1-dimensional nature of the Bartol simulation and by the fact that geomagnetic effects are ignored on propagation of the secondaries. Inclusion of these effects in the simulation is in progress (Coutu 1999). The influence of these effects on the atmospheric neutrino flux is thought to be small (Stanev, 1999) but needs to be quantified.

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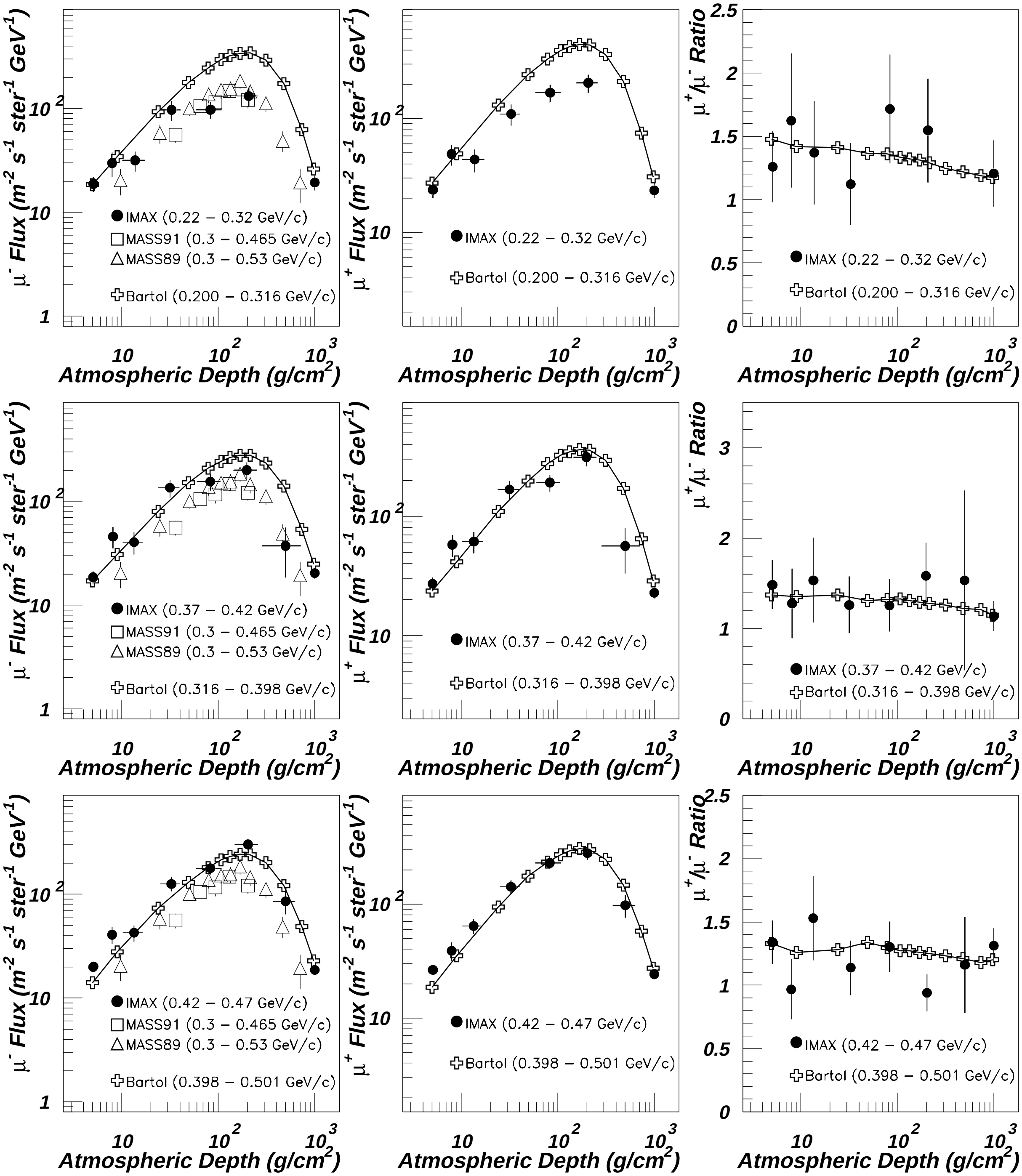

Figure 1: *The* μ^- *flux,* μ^- *flux, and* μ^+/μ^- *ratio as measured by IMAX (TOI) in the momentum ranges of* $0.22 \le p < 0.32$ *GeV/c (top figures),* $0.37 \le p < 0.42$ *GeV/c (middle figures), and* $0.42 \le p < 0.47$ *GeV/c (bottom figures). The predictions of the Bartol Monte Carlo (Barr, Gaisser, & Stanev, 1989; Stanev, 1999) which used the IMAX primary cosmic ray spectra as input and the results of two MASS flights (Bellotti et al., 1996; 1999) are superimposed.*