show that the average impulse energy would have been $k_B \times (0.24\ \mathrm{K})$. The lowest published value for room-temperature gravitational-wave detectors is $k_B \times (7.3\ \mathrm{K})$.[6]

For the data presented in this paper the decay time of the antenna mode was reduced by a defective accelerometer mounting. This has since been replaced, increasing the decay time by about an order of magnitude. Steps are also being taken to remove all sources of spurious noise. With these modifications, it should be possible to achieve an average impulse energy of $k_B \times (0.02\ \mathrm{K})$ with this antenna and transducer. If two such antennas were operated in coincidence, unpolarized gravitational radiation pulses of energy spectral density 60 J $\mathrm{m}^{-2}$ $\mathrm{Hz}^{-1}$ could be detected with an accidentals rate of 1 per day. The comparable spectral density for current room-temperature detectors[7] is $10^4$ J $\mathrm{m}^{-2}$ $\mathrm{Hz}^{-1}$.

These experiments have demonstrated that cryogenic gravitational wave antennas and transducers are practical. Work is proceeding on a 4500-kg antenna system using a microwave-pumped magnetometer. With this it should be possible to obtain a sensitivity approaching the ultimate limit for linear detectors.[8]

*This work supported under National Science Foundation Grant No. MPS 73-08748-A04.

†Alfred P. Sloan Fellow.

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# Observation of Prompt Single Muons and Dimuons in Hadron-Nucleus Collisions at 200 GeV/*c**

J. G. Branson, G. H. Sanders, A. J. S. Smith, and J. J. Thaler
*Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08540*

and

K. J. Anderson, G. G. Henry, K. T. McDonald,† J. E. Pilcher,‡ and E. I. Rosenberg
*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*

(Received 5 November 1976)

We trigger a large-acceptance spectrometer by single muons and observe any additional muons with good efficiency. The effect of $\pi$ and $K$ decays is subtracted to obtain the prompt muon signal in the kinematic region $0.1 < x < 0.4$ and $p_T < 1.0$ GeV/$c$. We find 0.7 ± 0.2 of all prompt $\mu$'s are produced in pairs; the $\mu/\pi$ ratio decreases with $x$ but increases with $p_T$, averaging $3 \times 10^{-5}$.

In a previous Letter[1] we have considered the contribution of muon pairs to the yield of single prompt muons and concluded that this contribution is large. In that work, only muon pairs were observed, and the corresponding inclusive single muon yield was obtained by a calculation. As part of our experimental program at Fermilab, we performed a short experiment in which the large-acceptance University of Chicago cyclotron magnet spectrometer was triggered by the production of a single muon, and any additional muons were detected with high probability. In this way we directly approach the important question: Are prompt muons produced in pairs?

The first works[2,3] to confront this question were based on estimates of prompt muons from decays of vector mesons; they concluded this source is insufficient to explain all prompt muons. Including the effect of the experimentally observed continuum of dimuons, we have been able to account for the bulk of the prompt single muons.[1] Leipuner *et al.*[4] observed both single muons and dimuons, concluding that the latter explain the former although the acceptance of the apparatus was such that the pairs-to-single ratio was 1/10.

Prompt muons are defined as those not resulting from the decay of $\pi$ and $K$ mesons. To separate prompt from decay muons we used the extrapolation method of previous workers.[5-7] The beam was incident on a short target which was followed by a thick hadron absorber. The distance between the target and absorber was varied to allow an extrapolation to zero decay path for mesons produced in the target and thus to eliminate muons from the decay of these mesons. Muons from the decay of mesons produced in secondary interactions in the absorber were eliminated by an additional extrapolation in decay path by a distance determined with a Monte Carlo calculation. The remaining muons are the desired signal consisting of prompt muons produced by primary interactions in the target as well as by secondary interactions in the absorber. Other workers have used the method of a variable-density target to extract the prompt muon signal.[5,8]

For this experiment only minor changes were made in the spectrometer described by Anderson *et al.*[9] A 200-GeV/$c$ proton beam of $10^5$/sec was used, defined by the following: no signal in either of two threshold Cherenkov counters set to detect $\mu$, $\pi$, and $K$ but not $p$; exactly one charged particle in beam-defining scintillation counters; and no charged particles in halo veto counters. The target was 2.5 cm of Fe followed by a $0.6\times5\times5$-cm scintillation counter. A signal in this counter of more than twice that of a minimum ionizing particle was required in the event trigger to indicate that the primary interaction took place in the target. The effect of backsplash from primary interactions which occurred in the absorber is considered below. The target and counter were moved as a unit during the variation of the decay path. The 2.15-m Fe hadron absorber was augmented by 17 cm of uranium at its front. The rest of the apparatus was unchanged. The single muon trigger was (proton in beam)$\cdot$(interaction in target)$\cdot$(count in a large scintillation-counter hodoscope which was preceded by 4000 g/cm$^2$ of material). We estimate that the fraction of triggers from muons in the beam was less than 1%.

Data were collected for three target-absorber separations: 5, 18, and 38 cm. For the 50 000 single muon triggers (mostly from $\pi$ decay), 1947 muon pairs were observed. Of these only 7 pairs had like-sign muons, which demonstrated that the pairs are almost entirely promptly produced, i.e., not from $\pi$ or $K$ decay.

We cross-normalize the three data sets to the same number of prompt muon pairs (opposite-sign minus same-sign). This procedure was possible since the relative change in the acceptance of the apparatus over the decay paths used was less than 2%.

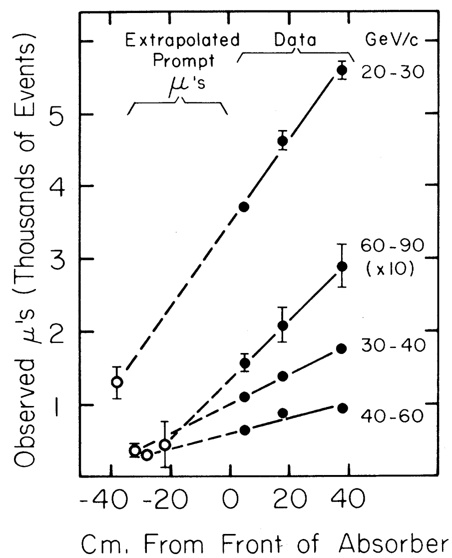


FIG. 1. The observed $\mu$ yield (solid circles) is plotted for the three positions of the target. The data for $\mu^+$ and $\mu^-$ have been combined. The prompt muon signal for target and absorber combined (open circles) is obtained by extrapolating the observed yield by the distances given in Table I to correct for $\pi$ and $K$ decay. This procedure includes the effect of secondary production which is larger at lower momenta. The data at the 18- and 38-cm positions have been normalized to that at 5 cm as described in the text.

The normalized yields of single muons (positive and negative combined) are shown in Fig. 1 as a function of decay path between the target and the absorber. Muons of less than 20 GeV/$c$ were excluded, for which the contribution of secondary interactions was greater than 60%. Muons of greater than 90 GeV/$c$ were excluded because of insufficient statistics for analysis, and also to avoid the effect of any residual muon contamination in the proton beam. These cuts reduced the data sample to some 13 000 single muons and 1100 pairs.

We now determine the prompt single muon signal for target and absorber production combined. To correct for the effect of $\mu$'s from decays of $\pi$'s and $K$'s produced in the target, we extrapolate the $\mu$ production curves shown in Fig. 1 into the absorber by 1 interaction length. This is the average available decay path for particles inside the absorber and is 18 cm for our U-Fe absorber. The essential feature of this procedure is that the slopes of the production curves are the numbers of decay muons which appear per centimeter of decay path, so that $N_{\rm decay}$ = (observed slope) ∘ (decay path). The method was extended to compensate for the effect of the decay of $\pi$ and $K$'s produced in the absorber by a suitable correction to the decay path, which was evaluated by a Monte Carlo simulation of the hadronic cascade. The effective decay path, $D$, is calculated to be $D = N_{\rm decay}/{\rm slope} = N_{\rm decay}/(N_{\pi K}/\Lambda)$, where now $N_{\rm decay}$ is the total number of $\mu$'s from the decay of both primary and secondary $\pi$'s and $K$'s (in a given momentum interval), $N_{\pi K}$ is the number of primary $\pi$'s and $K$'s which could decay into the proper-momentum $\mu$'s, and $\Lambda$ is the mean decay length in centimeters of these $\pi$'s and $K$'s. In this way, only a ratio is determined from the Monte Carlo calculation and it is therefore less sensitive to systematic errors. In other terms the effective decay path is approximately 1 interaction length divided by the fraction of muon parents which are produced in the target.

The program[10] CASIM was used for the cascade simulation and the results are summarized in Table I. The extrapolation distance, $D$, measured from the front of the absorber, is larger at lower momenta where the effect of secondary interactions is greater. The extrapolated prompt muon yields ($\mu^+$ and $\mu^-$ combined) for target and absorber together are shown in Fig. 1 and listed in Table I. The extrapolations were performed for $\mu^+$ and $\mu^-$ separately, and yield a prompt muon ratio of $\mu^+/\mu^- = 0.75 \pm 0.25$ averaged over the four momentum intervals.

The prompt muon yields are subject to a small correction for the backsplash effect mentioned earlier. Brief runs without the Fe target indicated that the fraction of triggers with the primary interaction in the absorber varied from 30% at the 5-cm target position to 5% at the 38-cm position. For these events the decay path available to primary $\pi$'s and $K$'s is reduced and fewer decay $\mu$'s appear. By use of the fractions of $\pi$'s expected to occur in the primary interaction given in Table I, we estimate a 5% loss of decay muons for all three target positions. The data have not been corrected for this effect.

The observed muon pair yield is now used to determine the fraction of prompt $\mu$'s which occur in pairs. In each momentum interval and for each target separation we accumulate the number of single muons coming from the observed pairs. These distributions are weighted by the normalization factors for the target positions and averaged (Table I). Finally, these singles yields are corrected for the detection probabilities of the companion muons, given in Table I, which include a factor of 0.92 for the efficiency of the chambers and the reconstruction program. The principal effect is that muons of less than 8 GeV energy are not detected. The acceptance was calculated assuming a $(1-X_F)^5$ distribution for the dimuons; use of a form $(1-X_F)^4$ would increase the acceptance by 3%. By comparison of the corrected singles yield from pairs to the total prompt singles yield we find the fraction of single muons produced in pairs to be $0.7 \pm 0.1$ averaged over the four momentum intervals. The error is statistical only. The fractions for each interval separately are given in Table I.

Systematic uncertainty in this result arises mainly in the extrapolation method used to obtain the total prompt $\mu$ signal, based on calculations with the Monte Carlo program CASIM. To obtain a measure of the reliability of this program we have compared it with another cascade calculation, FLUKA.[11] This calculation yielded extrapolation distances (10–15)% larger than CASIM and implies about 15% fewer prompt $\mu$'s. From this we conservatively estimate a systematic error of 25% in the prompt $\mu$ yield, and report the fraction of prompt $\mu$'s which occur in pairs as 0.7 $\pm$ 0.2, where now the uncertainty is predominantly systematic.

The data can be further analyzed to deduce the

TABLE I. Summary of the principal features of the analysis, including parameters calculated with the CASIM Monte Carlo program. See text for definitions of the parameters.

| MOMENTUM BIN (GeV/c) | EXTRAPOLATION DISTANCE (cm.) | PROMPT SINGLE $\mu$ | OBSERVED $\mu$ FROM PAIRS | SECOND $\mu$ DETECTION EFFICIENCY | FRACTION OF $\mu$ FROM PAIRS | $\pi/\mu$ SLOPE FACTOR (m.) | $\pi$ FROM TARGET | FRACTION OF $\pi$ FROM TARGET | $\mu/\pi$ |
|---|---|---|---|---|---|---|---|---|---|
| 20 - 30 | 38 | 1258 ± 209 | 493 ± 17 | 0.58 | 0.67 ± .11 | 1724 | $9.87 \times 10^6$ | 0.43 | $5.5 \pm 1.0 \times 10^{-5}$ |
| 30 - 40 | 32 | 356 ± 103 | 212 ± 11 | 0.60 | 0.99 ± .29 | 2944 | $5.87 \times 10^6$ | 0.52 | $3.2 \pm 1.0 \times 10^{-5}$ |
| 40 - 60 | 28 | 305 ± 70 | 138 ± 9 | 0.62 | 0.73 ± .17 | 5254 | $5.31 \times 10^6$ | 0.59 | $3.4 \pm 1.0 \times 10^{-5}$ |
| 60 - 90 | 22 | 45 ± 32 | 49 ± 5 | 0.64 | 1.72 ± 1.24 | 9096 | $3.65 \times 10^6$ | 0.68 | $0.8 \pm 0.6 \times 10^{-5}$ |

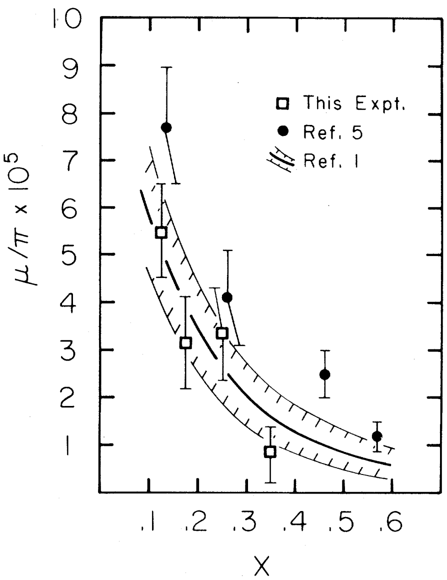


FIG. 2. The ratio prompt $(\mu^+ + \mu^-)/(\pi^+ + \pi^-)$ as a function of $x = p_L/p_{\text{beam}}$. The results of Refs. 1 and 5 have been converted from $\mu^-/\pi^-$ and $\mu^+/\pi^+$ assuming $\pi^+/\pi^- = 1 + 3.4x$, taken from Refs. 12 and 13. In this experiment and Ref. 5 all prompt $\mu$'s contribute, while for Ref. 1 only $\mu$ pairs are considered.

ratio of prompt muons to pions. The number of pions produced in the target (Table I) is obtained by multiplying the slopes of the curves in Fig. 1 by the slope factors listed in Table I which involve the $\pi$ decay length, the $K/\pi$ ratio, and relation between the spectra of decay muons and their parent pions. The number of prompt muons produced in the target is obtained from the total number of prompt muons by assuming that the fraction produced in the target is the same as the fraction of pions produced in the target. The Monte Carlo estimate of the latter quantity is also given in Table I.

The resulting ratios of prompt $(\mu^+ + \mu^-)/(\pi^+ + \pi^-)$ for the target only are shown in Fig. 2 and listed in Table I. The average for the four momentum bins is $(2.6 \pm 0.4) \times 10^{-5}$. Dividing the data into two bins of transverse momentum, we find $\langle \mu/\pi \rangle = (1.3 \pm 0.5) \times 10^{-5}$ for $p_T < 400$ MeV/$c$ ($\langle p_T \rangle = 250$ MeV/$c$), and $\langle \mu/\pi \rangle = (3.4 \pm 0.7) \times 10^{-5}$ for $p_T > 400$ MeV/$c$ ($\langle p_T \rangle = 650$ MeV/$c$). The systematic uncertainty in the $\mu/\pi$ ratios due to the use of the cascade calculation is estimated to be 40%. However the relative size of $\mu/\pi$ in the two $p_T$ bins is largely unaffected by this uncertainty.

Since we observe prompt $\mu$'s produced at any stage of the hadronic cascade, our signal includes $\mu$ pairs from the Bethe-Heitler process. A calculation of this effect shows that, at most, 15% of the prompt single muons in each momentum interval can be attributed to this source.

The picture of prompt muon production emerging from this study using a single $\mu$ trigger is generally consistent with that from our work using a pair trigger.[1] In the low-$p_T$ intermediate-$x$ region, prompt muons are produced principally in pairs. The ratio $\mu/\pi$ for the single prompt $\mu$'s is falling with $x$ but increasing with transverse momentum, with a typical value of $3 \times 10^{-5}$.

We wish to thank the staff of the Fermilab Neutrino Laboratory, directed by R. Lundy, for their support and technical assitance. The University of Chicago cyclotron magnet spectrometer was developed by the Chicago-Harvard-Illinois-Oxford collaboration, who kindly made it available to us for this experiment.

*Work supported in part by the U. S. Energy Research and Development Administration and by the National Science Foundation. The experiment was performed at the Fermi National Accelerator Laboratory.

†Enrico Fermi Postdoctoral Fellow. Present address: Joseph Henry Laboratories, Princeton University, Princeton, N. J. 08540.

‡Alfred P. Sloan Foundation Fellow.

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