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"CLOUD" AND "SURFACE" MUON BEAM CHARACTERISTICS*

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ABSTRACT

Muon rates and polarizations have been measured on several beam channels at LAMPF to characterize muon production from the primary target surface or adjacent volume. To produce these "surface" or "cloud" beams, the channel is tuned to accept beam directly from the target. The measurements range from 20-200 MeV/c in muon momentum at production angles of 20, 45, and 65°. Both μ^+ and μ^- rates, and μ^+ polarization were measured. Surface beam polarization is close to 100%, while cloud beam polarization is low. The surface μ^+ rate dependence upon proton beam depth in the target was studied.

I. INTRODUCTION

A beam channel tuned for delivery of low-momentum pions will also deliver a substantial muon flux from pion decays in or near the pion production target. Surface muon beams, from π^+ mesons stopping and decaying in the target surface, have been recently developed and used.[1,2] In Section II we report on rate studies of both surface and cloud beams at LAMPF. In Section III the rates are reduced to phase-space densities, giving a common basis for comparisons and predictions of channel performance. The muon polarization data are given in Section IV. Reference 3 provides a detailed analysis of direct muon beam source characteristics, and more comparisons with conventional muon beams.

II. MEASURED RATES

The Low-Energy Pion Channel (LEP) was chosen to study direct μ production in detail because the channel angular acceptance $\Delta\Omega$ and momentum bite Δp can be controlled and the optics is relatively well understood. In addition, the short channel length of 14 m permits a measurable pion flux to be delivered at low energies ($c\tau_\pi$ = 7.8 m = decay length for $p_\pi = m_\pi$). The LEP channel jaws were set for 1% momentum bite and 10-msr acceptance, both well within the full-channel limits.

A vacuum extension to the channel contained the π-μ counters, eliminating all material between production target and detectors. The in-vacuum apparatus consisted of a 0.25-mm scintillator and a 1.6-mm scintillator, both 6 cm square. A multiwire proportional chamber (MWPC) was placed on the air side of a thin exit window, followed by an absorber and a large electron veto scintillator. Surface muons were counted by pulse-height-identification alone. The π rate was negligible, and the copious low-energy protons did not penetrate to the second counter to give a coincidence count. At higher momenta, and for negative beams, particle identification was achieved by time-of-flight (TOF) relative to the accelerator rf signal by means of special 40-ns proton beam pulse chopping. By this means, TOF is measured in effect from the primary production target. The pion and cloud muon rates were determined from counts within the narrow timing peaks after background subtraction. Muons produced by in-channel decays are counted as background in this method.

The 800-MeV proton beam current 0.25 μA_{av} was monitored by a secondary-emission foil. The pions were produced from a 3-cm, 5.2-g/cm^2 carbon target. Figures 1 and 2 show the measured rates vs channel momentum p. The pions scale closely as p^3 times a decay factor, as expected for a channel operated at constant percentage momentum bite and receiving a pure phase-space distribution ($\sim p^2$). The cloud μ rate scales roughly as p^3. The surface μ^+ rate is 20-30 times the cloud μ^+ rate just above 30 MeV/c. The statistical errors on the measured data are small ($\lesssim 3\%$). Systematic effects give an estimated $\pm 5\%$ error on each point, and $\sim \pm 10\%$ error on overall normalization.

The dependence of the surface muon rate upon proton beam depth R beneath the target surface is shown in Fig. 3. Evidently the beam should be close to the target surface to enhance surface μ^+ production, as expected because the exponent in the range relationship, $R \sim p^{3.6}$ is higher than the pion production phase-space exponent, p^2. The density of stopping pions is $(dN/dR) = (dN/dp)(dp/dR) \sim R^{-1/6}$.

At lower channel momenta, the mesons do not effectively penetrate the MWPC. The beam spot size as measured on the wire chamber reflects principally the electron component, and was observed to be 17 mm FWHM in the channel dispersion plane.

The μ^+ surface beam and μ^- cloud beam rates were measured[4] on the LAMPF Stopped Muon Channel (SMC) with an apparatus similar to that used on LEP. The rates are shown in Fig. 4 with a comparison to the rates obtainable from a conventional μ-"decay" beam. The spot size measured at 60 MeV/c was 11 cm in the channel dispersion plane by 7.6 cm in the other plane.

III. ANALYSIS

The measured pion rates on LEP were converted to absolute cross sections, shown in Fig. 5. The same procedure was applied to the muon rates to give an apparent cross section; the variation of this number with target and channel geometry is of interest. The cross sections are given as phase-space densities, $d^3\sigma/dp^3$, to reveal departures from pure phase-space behavior.

Several conclusions are apparent from this display:

1. the overall normalization is in fair agreement with previously measured[5] production cross sections for low-energy pions at 730-MeV proton beam energy;
2. pion production scales closely with phase space;
3. cloud μ's scale with phase space within $\pm 15\%$; and
4. surface μ apparent phase-space density is actually higher than the pion density.

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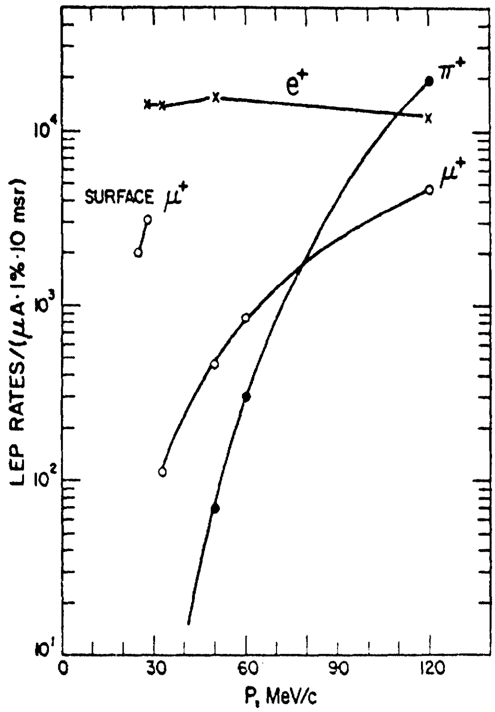

Fig. 1. Positive-beam rates per second on LEP (3-cm carbon production target; 800-MeV proton primary beam).

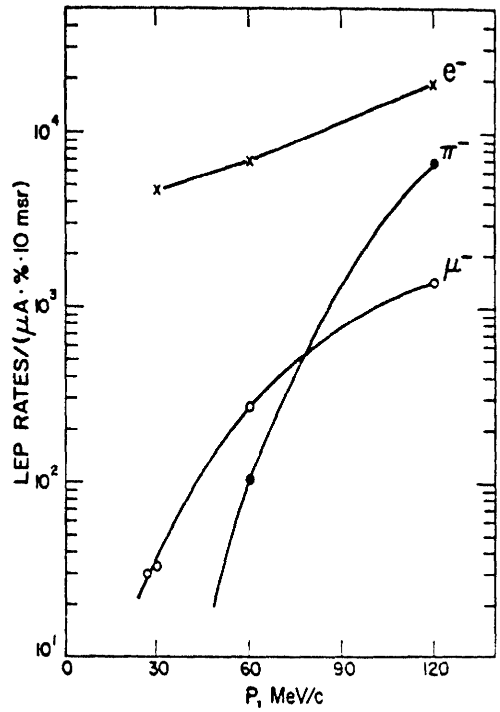

Fig. 2. Negative-beam rates per second on LEP.

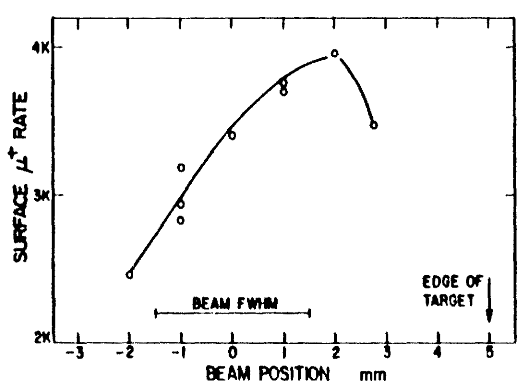

Fig. 3. Surface μ^+ rate on LEP as a function of proton beam depth beneath target edge.

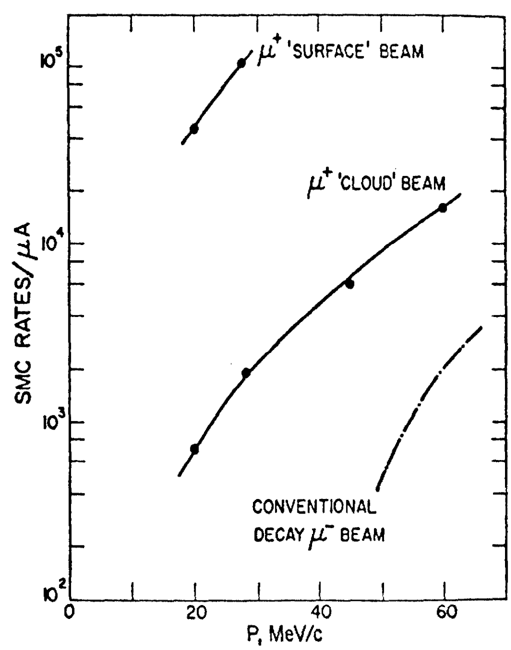

Fig. 4. Surface μ^+ and cloud μ^- rates per second on SMC (6-cm carbon production target). Conventional "decay" beam rate is shown for comparison.

The SMC data were also converted to phase-space density and plotted in Fig. 5. The channel acceptance and solid angle are known with less confidence for this large-aperture channel. Nominal figures of 8% and 30 msr produces reasonable agreement with the LEP surface muon phase-space density. The SMC cloud μ-'cross sections' are 20-100% higher than on LEP.

The qualitative features of the muon spectra are predicted by Eq. 20 of Ref. 3, which may be rewritten in the form

$$d^3\sigma_\mu/dp_\mu^3 = G(d^3\sigma_\pi/dp_\pi^3)_{av} \quad ,$$

where G is a factor containing the geometry of the secondary channel. The indicated average of the pion cross section is over the pion phase-space volume contributing to the particular muon momentum p_μ. The data reported here and in Ref. 5 show that $d\sigma_\pi/(p^2dp)$ is approximately constant, and $d\sigma_\pi/d\cos\theta_\pi$ has only factor-of-2 variation over the portion of the π spectrum which can contribute to low-energy muon production. The greater production of μ^-

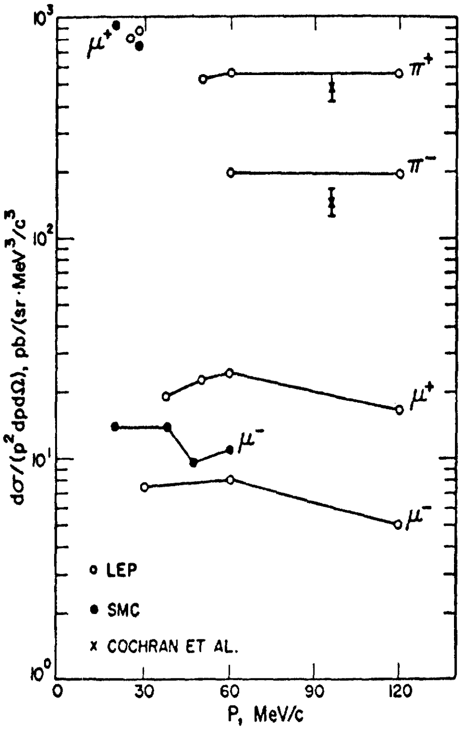

Fig. 5. Cross sections for pion production, and effective cross sections for surface and cloud muon production, (Cochran *et al.* = Ref. 5.)

relative to surface μ^+, comparing SMC to LEP, is presumably a result of the larger channel aperture (30 cm vs 20 cm) in SMC. Reference 3 provides an analysis of other factors influencing the cloud/surface ratio such as beam depth in target and secondary channel angle. The LEP production angle is 45°; SMC is at 65°. Both targets are carbon but the shapes are different.

IV. POLARIZATION

The polarization of the cloud and surface μ^+ beams was measured on LEP with a "muon spin rotation" (μSR) apparatus consisting of a muon target, a Helmholtz coil, and "left-right" electron counters.

Surface beam polarization was measured to be close to 100%. (Muons produced by pion decays at rest are 100% polarized. There is a few percent cloud contribution to the surface beam flux and some small depolarization in the muon target.) The cloud beam polarizations were normalized to the surface beam polarization ($\equiv -1$) and are plotted in Fig. 6. The prediction from Ref. 3 is also shown.

Cloud μ polarization was also measured with the μSR apparatus on a 20° beam line (P^3) at 90 and 200 MeV/c. The observed polarizations were very low.

The conventional "decay" muon channel first selects pion momentum, then muon momentum p_μ from forward or backward π decays. These beams will have high polarization. In the cloud beam, without selection of pion momentum, both forward and backward decays contribute to the muon flux, thus reducing polarization.

V. CONCLUSIONS

The data allow accurate specification of cloud and surface beam characteristics on the channels studied. The

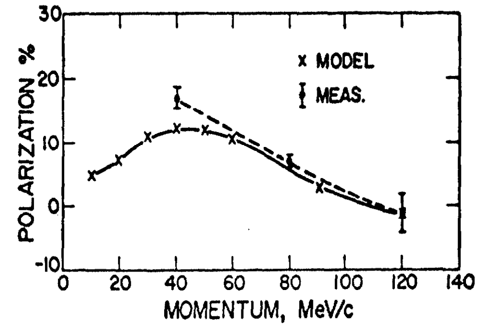

Fig. 6. μ^+ polarization measured on LEP. Model is Ref. 3 calculation.

potential for these beams of high stopping density is so promising that extensive channel modifications are planned or under way on P^3 and SMC to enhance their use, including a beam separator and phase-space tailoring hardware for SMC.

More generally, the reduction to phase-space densities shows that the low-energy pion flux scales as phase space in momentum and the same is approximately true for the muons. Table I gives the π cross sections measured on LEP and the range of effective μ cross sections covering both LEP and SMC. The μ/π ratio of 3-9% may provide a useful estimator of cloud muon production for new channels and other beam energies.

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TABLE I

CROSS SECTIONS FOR PION AND DIRECT MUON PRODUCTION FROM 800-MeV PROTONS ON CARBON

Particle	$d^3\sigma/dp^3$, pb/(sr · MeV^3/c^3)
π^+ (45°)	560 ± 10%
π^- (45°)	197 ± 10%
μ^+ (surface)	700 - 900
μ^+ (cloud)	160 - 400
μ^- (cloud)	50 - 140