PARTICLE PRODUCTION BY 10-30 Bev PROTONS INCIDENT ON Al AND Be†

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High-energy secondary particles produced by the nuclear interactions of 10-30 Bev protons have been investigated at the Brookhaven alternating gradient synchrotron (AGS).[1] This experiment was carried out with aluminum and beryllium internal targets (according to availability) at production angles[2] of $4\frac{3}{4}°$, 9°, 13°, and 20°. The momentum of the particles in a beam was selected by magnetic deflection and the velocities determined with focusing, gas Čerenkov counters.[3] The momentum acceptance and angular divergence of the beams were fixed by scintillation counter telescopes. Typical values of these parameters were $\Delta p/p \simeq \pm 2\,\%$ and $\Delta\Omega \simeq 2\times10^{-7}$ steradian. The ratio of quadruple coincidences ($S_1S_2S_3C$) to triple coincidences ($S_1S_2S_3$) corrected when necessary for Čerenkov counter inefficiency gave the relative abundance of the particle of selected mass in a beam.

Most of the data were taken with the machine operated at 29.5 ± 0.5 Bev with an average intensity of $\sim 4\times10^{10}$ protons per pulse accelerated each 2.4 seconds. Measurements were also made at AGS energies of 25, 20, and 10 Bev, at which energies the machine can be operated at 2.0-, 1.6-, and 0.8-second repetition periods, respectively.

Figure 1 shows the momentum distributions of protons, π^+ and π^- mesons, corrected for π decay between the target and the final scintillator in order to represent the pion-production rates at the target. A rough correction has been made for the number of decay muons counted as pions. This correction was less than 5% of the measured pion intensity for beams of momentum >4 Bev/c. The muon contamination increased rapidly with decreasing momentum below 4 Bev/c; at 2.5 Bev/c the contamination was ~12% and at 1.25 Bev/c it

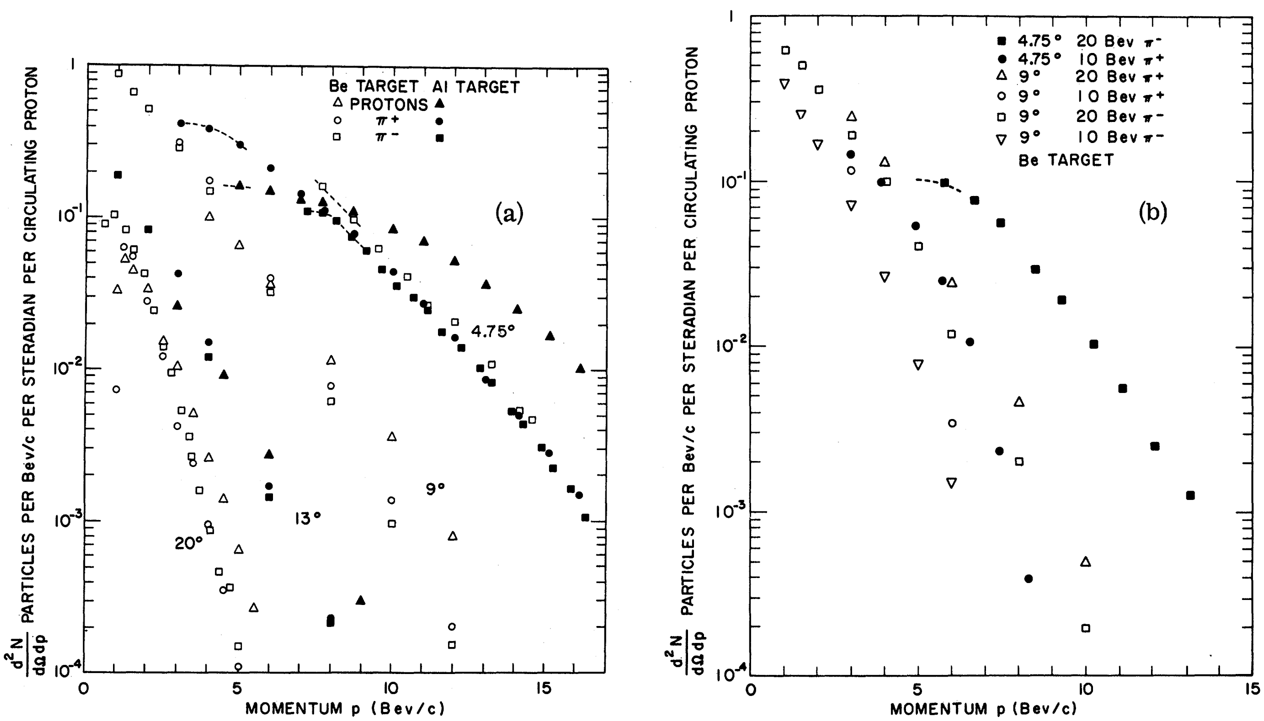

FIG. 1. The momentum spectra, (a) of $\pi^\pm$ mesons and protons for 30-Bev incident proton energy, and (b) of $\pi^\pm$ mesons for 10- and 20-Bev incident proton energies. The ordinate is the number of particles per steradian per Bev/c per circulating proton. The dashed portions of the $4\frac{3}{4}°$ spectra indicate the regions where the correction due to fringing field effects exceeds 15% of the measured value of $d^2N/dpd\Omega$.

was ~40%. The curves are normalized to the number of circulating protons in the AGS which has been calibrated by electrical methods to an accuracy of about 25%.[4] The effective target thickness for nuclear interactions was measured by radiochemical methods for both Al and Be targets.[5] The efficiencies of the targets have been estimated by Courant.[6] For Al the effective target thickness was 37 ± 7 g/cm^2, and for Be it was 21 ± 3 g/cm^2, corresponding to an efficiency for each target of ~50%. Thus, $2 \times d^2N/dpd\Omega$ approximately represents the number of particles produced per inelastic interaction with the target nucleus per steradian per Bev/c. Fluctuations in target efficiency may have been as much as ±10%.

Of the four beams measured, the magnetic field of the AGS strongly influences only the trajectory of the nominal $4\frac{3}{4}°$ beam. Thus in this beam the actual production angle varies from $3\frac{3}{4}°$ for negative particles of momentum 6 Bev/c to $5\frac{1}{2}°$ for positive particles of momentum 2 Bev/c; the production angle is 4.7° for very high momentum (i.e., ~20 Bev/c) particles of either sign of charge.[7] The fringing field of the AGS and the beam collimator combine to reduce the effective solid angle seen by the counter telescope. Corrections for these effects have been applied to the measured data; the dashed portions of the $4\frac{3}{4}°$ curves indicate the regions where these corrections exceeded 15%. Figures 2 and 3 and Table I show the ratios of the intensities K^+/π^+, K^-/π^-, and $\bar{p}/\pi^-$, measured in each beam at various momenta. The ratios measured experimentally have been corrected for K and π decay between the target and the final scin-

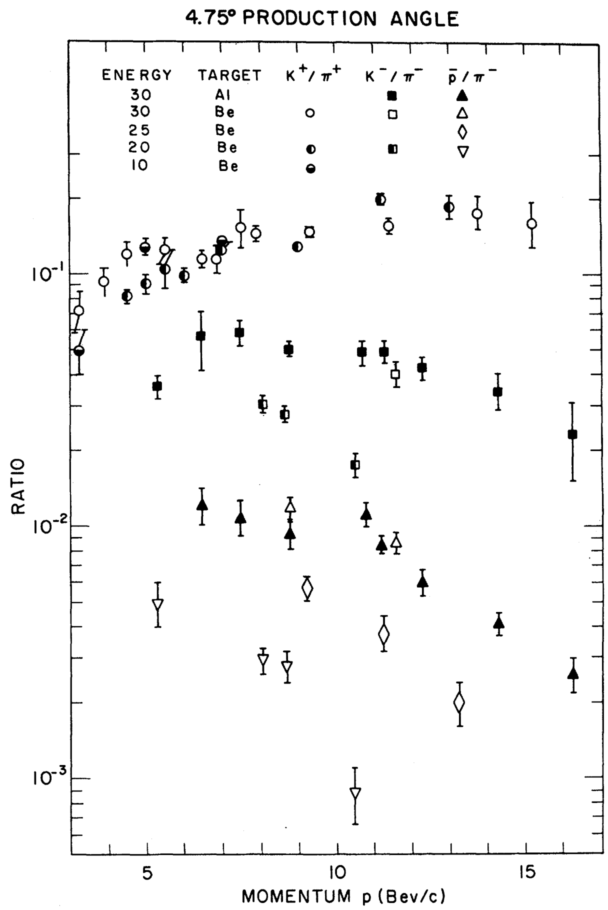

FIG. 2. The production ratios at the target of K^+/π^+, K^-/π^-, and $\bar{p}/\pi^-$ at various momenta, at $4\frac{3}{4}°$ production angle. The ratios have been corrected for K and π decay between the target and the final scintillator and for muon contamination.

Table I. The production ratios at the target of K^+/π^+, K^-/π^-, and $\bar{p}/\pi^-$ at various momenta for production angles of 13° and 20°. The AGS internal energy = 30 Bev. The ratios have been corrected for K and π decay between the target and the final scintillator and for muon contamination.

Production angle	Target	Momentum (Bev/c)	Production ratio, at target K^+/π^+	K^-/π^-	$\bar{p}/\pi^-$
13°	Al	3.0	0.27 ±0.02		
		4.5			0.013 ±0.002
		6.0	0.29 ±0.05	0.062 ±0.010	0.014 ±0.002
		9.0	0.31 ±0.04	0.048 ±0.010	0.013 ±0.007
20°	Be	1.25	0.027 ±0.012	0.012 ±0.005	
		2.5	0.230 ±0.012	0.088 ±0.009	0.0051 ±0.0015
		3.0		0.088 ±0.010	

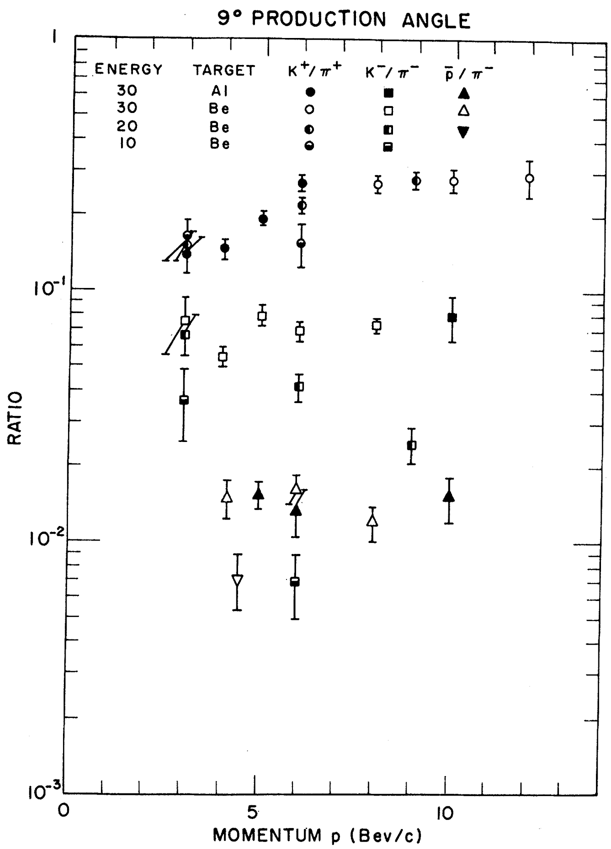

FIG. 3. The production ratios at the target of K^+/π^+, K^-/π^-, and $\bar{p}/\pi^-$ at various momenta, at 9° production angle. The ratios have been corrected for K and π decay between the target and the final scintillator and for muon contamination.

tillator so that the values plotted represent the production ratios at the target.

It can be seen from Fig. 1 that, where comparisons can be made, the characteristics of the pion spectra from the beryllium target and from the aluminum target are almost the same, except that

$$\left(\frac{d^2N}{dp d\Omega}\right)_{\rm Be} \Big/ \left(\frac{d^2N}{dp d\Omega}\right)_{\rm Al} \approx 1.1 - 1.4.$$

Part of these apparent differences between Al and Be targets may be due to relative monitoring and beam normalization errors and to fluctuations in target efficiency. The ratios K^+/π^+, K^-/π^-, and $\bar{p}/\pi^-$ can be seen from Figs. 2 and 3 to be insensitive to the difference between an aluminum and a beryllium target. In view of this insensitivity of particle production to target material and from general considerations based on the optical model, it appears that an analysis of the data in terms of a collision of the incident proton with a single nucleon of the target nucleus may be of interest and may reveal some significant characteristics of high-energy proton-nucleon interactions.

If one transforms the pion spectra to the proton-nucleon c.m. system, one finds that the pion spectra exhibit a low-energy peak $\lesssim 500$ Mev/c in the c.m. system, although the available kinetic energy ≈ 6 Bev. Furthermore the angular distribution is peaked in the forward direction. The c.m. angular and momentum distributions of the pions appear to be consistent with a limited mean transverse momentum transfer $\lesssim 0.5$-1 Bev/c.

From Figs. 2 and 3 it is clear that the K^+/π^+ ratios are not strongly sensitive to incident proton energy and tend to increase toward higher K^+ momenta. For 20-30 Bev incident proton energy, typical measured values of the K^+/π^+ ratio vary from 0.05 to 0.3. On the other hand, the K^-/π^- ratio falls rapidly with decreasing incident proton energy and also falls rapidly with increasing K^- momentum. Typical measured values of the K^-/π^- ratio vary from 0.08 to 0.02. At a given production angle the K^-/π^- and K^+/π^+ ratios tend to approach equality at very low momenta. These results may imply that the production of low-momentum K mesons occurs predominantly through K-pair production, while in the production of high-momentum K^+ mesons associated production (K-hyperon production) predominates.

For $\bar{p}/\pi^-$ ratios typical values are ~0.01-0.015 at low $\bar{p}$ momenta, falling to ~0.001 at high momenta. The $\bar{p}/\pi^-$ ratios are sensitive to the incident proton energy, dropping rapidly at the higher $\bar{p}$ momenta when the incident proton energy is reduced from 30 Bev to 20 Bev. This result is understandable when one recalls that the $\bar{p}$-p threshold in the c.m. system is 1.88 Bev.

Comparisons can be made between the results presented here and the results of some investigations[1] performed at CERN at 25-Bev proton energy using an Al target. At 6° lab production angle, three CERN K^-/π^- ratios were reported —at 5, 6, and 8 Bev/c. These data seem to lie reasonably between our data at 30-Bev and 20-Bev incident proton energy. Of the four CERN K^+/π^+ ratios reported by von Dardel et al.,[1] the ratio at 5 Bev/c is higher than our result by a factor ≈ 1.5. However, the CERN K^+/π^+ ratios at 6 and 8 Bev/c agree reasonably well with our results.

The CERN $\bar{p}/\pi^-$ ratios at 6° lab production angle, at 6, 8, and 11 Bev/c, are in agreement with our data, but the CERN point at 16 Bev/c appears to be higher than the trend of our data. The $\bar{p}/\pi^-$

ratios measured at CERN at 16° lab production angle by Cocconi et al.[1] are reasonably consistent with the trend of our measurements at production angles of 13° and 20°.

A more complete account of this work will be published elsewhere.

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[2]The $4\frac{3}{4}$° and 20° experiments were performed by S. J. Lindenbaum, W. A. Love, J. A. Niederer, S. Ozaki, J. J. Russell, and L. C. L. Yuan. The 9° and 13° experiments were performed by W. F. Baker, R. L. Cool, E. W. Jenkins, T. F. Kycia, D. Lüers, and A. L. Read.

[3]The Čerenkov counters are described in D. A. Hill, D. O. Caldwell, D. H. Frisch, L. S. Osborne, D. M. Ritson, and R. A. Schluter, Rev. Sci. Instr. 32, 111 (1961); T. F. Kycia and E. W. Jenkins, paper presented at the International Conference on Nuclear Electronics at Belgrade, Yugoslavia, May, 1961 (unpublished), and Brookhaven National Laboratory Report BNL-5493 (unpublished); S. J. Lindenbaum and L. C. L. Yuan, in Methods of Experimental Physics (Academic Press, Inc., New York, to be published), Vol. 5A, Sec. 1.5.1; and S. J. Lindenbaum, W. A. Love, J. A. Niederer, S. Ozaki, J. J. Russell, and L. C. L. Yuan (to be published).

[4]H. J. Halama, Brookhaven National Laboratory Accelerator Development Department Internal Report HJH-1 (unpublished), and private communication.

[5]J. B. Cumming, G. Friedlander, J. Hudis, and A. Poskanzer (private communication).

[6]E. D. Courant (private communication).

[7]These remarks are based on the results of the IBM-704 program BEAM written by E. D. Courant [Brookhaven National Laboratory Accelerator Development Department Internal Report EDC-36 (unpublished), and private communication].

FAST ATOMIC TRANSITIONS WITHIN μ-MESONIC HYPERFINE DOUBLETS, AND OBSERVABLE EFFECTS OF THE SPIN DEPENDENCE OF MUON ABSORPTION*

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It has been pointed out by Bernstein, Lee, Yang, and Primakoff,[1] that the two members $F_\pm = I \pm \frac{1}{2}$ of the hyperfine doublet ground state of a μ-mesonic atom with nonzero nuclear spin I could exhibit different disappearance rates $\Lambda_\pm$ as a consequence of the possible spin dependence of the interaction responsible for muon absorption. In particular, the now currently favored "universal" V-A interaction would lead to $\Lambda_+ < \Lambda_-$. Bernstein et al.[1] made the implicit assumption that atomic processes inducing transitions between the two states $F_\pm$ were negligibly slow. With this assumption, they predicted that a logarithmic plot of the time dependence of the electron rates from negative muons stopped in a monoisotopic target of nonzero I should exhibit a positive curvature, corresponding to the superposition of the two exponentials characterized by Λ_+ and Λ_-. Experimental detection of such a curvature could serve as a proof of the spin dependence of the absorption interactions but would give no clue to its more detailed nature.

It was subsequently pointed out[2] that, at least for the targets of experimental interest, the assumption of a negligibly slow transition rate between the two states $F_\pm$ is not a valid one. It was shown that the magnetic interaction between the "core" (=nucleus + muon) of the mesonic atom and its outer s electrons provides a sizeable conversion rate R between those two states. An explicit calculation for the case of ${}_{13}Al^{27}$ was presented in reference 2, made under the assumption that only the 3s (conduction) electrons of this target would effectively contribute to R. The magnitude of R so calculated was comparable to that of the difference $|\Lambda_- - \Lambda_+| \equiv |\Delta\Lambda|$. As was emphasized in reference 2, this parent-daughter relationship would lead to a negative curvature in the