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Publication Date
1950-03-08

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Keith A. Brueckner

March 9, 1950

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Production of π-Mesons in Nucleon-Nucleon Collisions

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March 9, 1950

The production of mesons in nucleon-nucleon collisions has been studied in considerable detail by a number of theoretical workers.[1] Experiments are now being carried out at Berkeley[2] which give information about the production of charged and neutral mesons by neutron-proton and proton-proton collisions. The calculations which have been made for the various mesons theories do not in general give results which can be compared with the experimental measurements. Specifically, the separate cross sections for neutral and charged meson production and the differential energy and angular dependence of the cross sections have not been given. We therefore have calculated the differential cross sections for production of charged or neutral mesons in n-p and p-p collisions, for scalar meson theory, pseudoscalar meson theory with pseudoscalar and pseudovector coupling, and vector meson theory with vector coupling. These calculations are made in the center-of-mass coordinate system for energies near threshold, and corrections of the order v^2/c^2 for the mesons or nucleons are neglected. The results are subject to the large uncertainties of the weak coupling approximation applied to meson theory, but it is hoped that they are at least qualitatively correct.

A Feynman-Dyson diagram for meson production is given in Figure 1. Seven additional diagrams may be obtained for emission of the meson by the three other

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[1] For references see Cecile Morette, Phys. Rev. 76, 1432 (1949)

[2] C. Richman and H. Wilcox, Bull. Am. Phys. Soc. 24, No. 8 (1949)
R. Bjorkland, W. E. Crandall, B. J. Moyer, H. F. York, Phys. Rev. 77, 213 (1950)

nucleons and for corresponding diagrams in which the two initial or final nucleons are interchanged. Subject to charge conservation, however, some of these diagrams are forbidden for the production of charged mesons. The matrix element[3] representing the diagram of Figure 1 is

1) $$\Psi^+(3)\left[U^2_\mu \frac{1}{(P_1-q)_\mu \gamma_\mu - i} U^1_\nu\right]\Psi(1) \qquad \frac{\Psi^+(4)\, U^1_\nu \Psi(2)\, \Phi_\mu(q)}{\left[(P_4-P_2)^2+\mu^2\right]}$$

where

2) $U^2_\mu = U^1_\mu = \delta_{\mu o} g i$ scalar

3) $= \delta_{\mu o} g \gamma_5$ pseudoscalar, pseudoscalar coupling

4) $U^2_\mu = \delta_{\mu o} \frac{\gamma_5}{\mu} q_\nu \gamma_\nu g$

$U^1_\mu = \delta_{\mu o}\, g \frac{\gamma_5}{\mu} (P_4-P_2)_\nu \gamma_\nu$ pseudoscalar, pseudovector coupling

5) $U^2_\mu = U^1_\mu = \gamma_\mu g$ vector

6) $\Phi_\mu = \Phi\, \delta_{\mu o}$ scalar, pseudoscalar

7) $\Phi_\mu = \Phi_\mu$ vector

The additional seven matrix elements can be obtained by various permutations of P_1, P_2, P_3, P_4 and changes of the sign of q. These matrix elements are approximately in the center-of-mass system

8) $$\frac{1}{\mu^2\sqrt{2\mu}}\left[\Psi^*(3)\,\Psi(1)\right]\left[\Psi^*(4)\,\Psi(2)\right]$$ scalar

9) $$\frac{1}{4\mu\sqrt{2\mu}}\left[\Psi^*(3)\,\Psi(1)\right]\left[\Psi^*(4)\vec{\sigma}\cdot\vec{P}_2\,\Psi(2)\right]$$ pseudoscalar, pseudoscalar coupling

10) $$\frac{1}{\mu^3\sqrt{2\mu}}\left[\Psi^*(3)\sigma\cdot q\ \sigma\cdot P_1\,\Psi(1)\right]\left[\Psi^*(4)\sigma\cdot P_2\,\Psi(2)\right]$$ pseudoscalar, pseudovector coupling

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[3] We set M(nucleon mass) = $\hbar$ = C = 1.

11) $\frac{|\vec{q}|}{\mu^3\sqrt{2\mu}}\,[\Psi^*(3)\,\Psi(1)][\Psi^*(4)\,\Psi(2)]$ vector, vector coupling

except for possible multiplicative factors of -1, $\sqrt{-1}$, and the third power of the coupling constant for the charged or neutral meson field.

The differential cross section in the center-of-mass system then is, to the approximation used here,

12) $\frac{d\sigma}{d\Omega dT} = \frac{\sqrt{2}\,2\mu}{(4\pi)^3\pi}\,|M|^2\sqrt{T(T_M-T)}$ (x 1/2 for identical final nucleons)

where T = kinetic energy of meson in center-of-mass system, T_M = maximum kinetic energy of meson in center-of-mass system. The values of $|M|^2$ are given in Table 1. It is interesting to observe that the only theory which gives production of neutral mesons with a cross section comparable with that for charged mesons is the pseudoscalar theory with pseudoscalar coupling. For the other theories for neutral meson production, cancellations occur between matrix elements corresponding to emission of the final meson before or after scattering which make the cross section the order of $(\mu/M)^2$ smaller than for charged production.

Using these values for the matrix elements the differential cross sections for production of positive mesons in p-p collisions are

13) $\frac{d\sigma}{d\Omega dT} = 1.22 \times 10^{-27}\,\frac{\sqrt{T(T_m-T)}}{(\mu c^2)^2}$

$\left\{\begin{array}{l}\frac{g^2}{4\pi\hbar c} = .529 \quad \text{scalar} \\ \frac{(g^2(g^2+2g_o^2)2)^{1/3}}{(4\pi\hbar c)} = 8.86 \\ \text{pseudoscalar with pseudoscalar} \\ \text{coupling}\end{array}\right.$

$= 1.45 \times 10^{-26}\,\frac{T\sqrt{T(T_m-T)}}{(\mu c^2)^3}$

$\left\{\begin{array}{l}\frac{g^2}{4\pi\hbar c} = .269 \quad \text{pseudoscalar} \\ \text{with pseudovector coupling} \\ \\ \frac{g^2}{4\pi\hbar c} = .925 \quad \text{vector with} \\ \text{vector coupling}\end{array}\right.$

The value of $g^2/4\pi\hbar C$ has been selected arbitrarily to give a total cross section at 350 Mev of 2×10^{-28} cm^2 for production of positive π-mesons in p-p collisions. The cross sections for production of charged mesons in n-p collisions then are 1/2 of these; for production of neutral mesons, the cross sections can be obtained by substitutions from Table 1. The total cross sections obtained by integration over energy and angle are related to those above by

14)
$$\int d\Omega \int_0^{T_m} dT \sqrt{T(T_m - T)} = \frac{\pi^2}{2} T_m^2$$

$$\int d\Omega \int_0^{T_m} dT \, T\sqrt{T(T_m - T)} = \frac{\pi^2}{4} T_m^3$$

The maximum meson kinetic energy in the center-of-mass system T_m is related to the incident nucleon kinetic energy in the laboratory system T_o by

15)
$$\mu C^2 + T_m = 2M\left[\sqrt{1 + \frac{T_o}{2MC^2}} - 1\right] \qquad (M = \text{nucleon mass})$$

The differential cross sections in the laboratory system given by these results are plotted in Figures 2 and 3. The total cross sections are given in Figure 4. For nucleons bombarding nucleons at rest, the approximations made in deriving these results are probably good for incident nucleon energies less than 350-400 Mev corresponding to maximum meson kinetic energies in the center-of-mass system of 26-48 Mev.

This work was performed under the auspices of the Atomic Energy Commission.

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Table 1

Square of magnitude of matrix element for meson production according to scalar theory (Sc), pseudoscalar theory with pseudoscalar (Ps Ps) or pseudovector (Ps Pv) coupling, and vector theory with vector coupling (V V). g is the coupling constant for charged mesons, g_o the coupling constant for neutral mesons.

	Sc $(\times \frac{1}{2\mu^5})$	Ps Ps $(\times \frac{1}{32\mu^2})$	Ps Pv $(\times \frac{T}{\mu^8})$	V V $(\times \frac{T}{\mu^6})$
Charged meson	g^6	$g^2(g^2+2g_o^2)^2$	g^6	g^6
n-p, neutral	0	$8g_o^2(g^4+g_o^4)$	0	0
p-p, neutral	0	$16g_o^6$	0	0

Captions

Figure 1. Diagram for meson production in lowest order.

2. Differential cross section for production of positive scalar mesons or pseudoscalar mesons with pseudoscalar coupling by 350 Mev protons bombarding protons at rest. The energy indicated is the kinetic energy of the meson.

3. Differential cross section for production of positive pseudoscalar mesons with pseudovector coupling or vector mesons with vector coupling.

4. Variation of total cross section for positive meson production with energy of incident nucleon for p-p collisions. The solid curve is for scalar mesons or pseudoscalar mesons with pseudoscalar coupling; the dashed curve is for pseudoscalar mesons with pseudovector coupling or vector mesons with vector coupling.

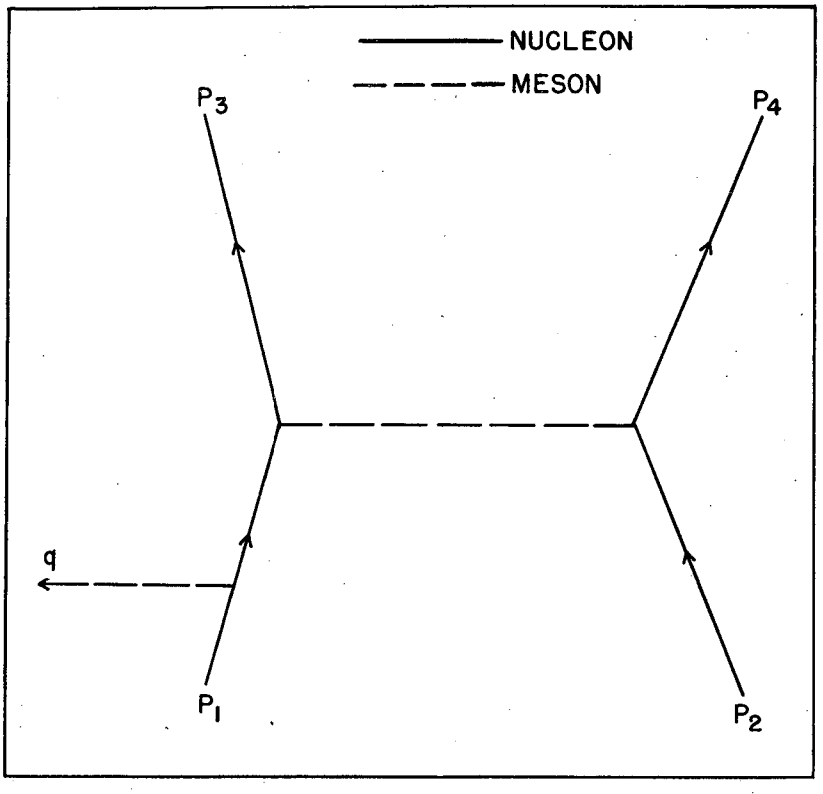

FIG. 1 Mu 61

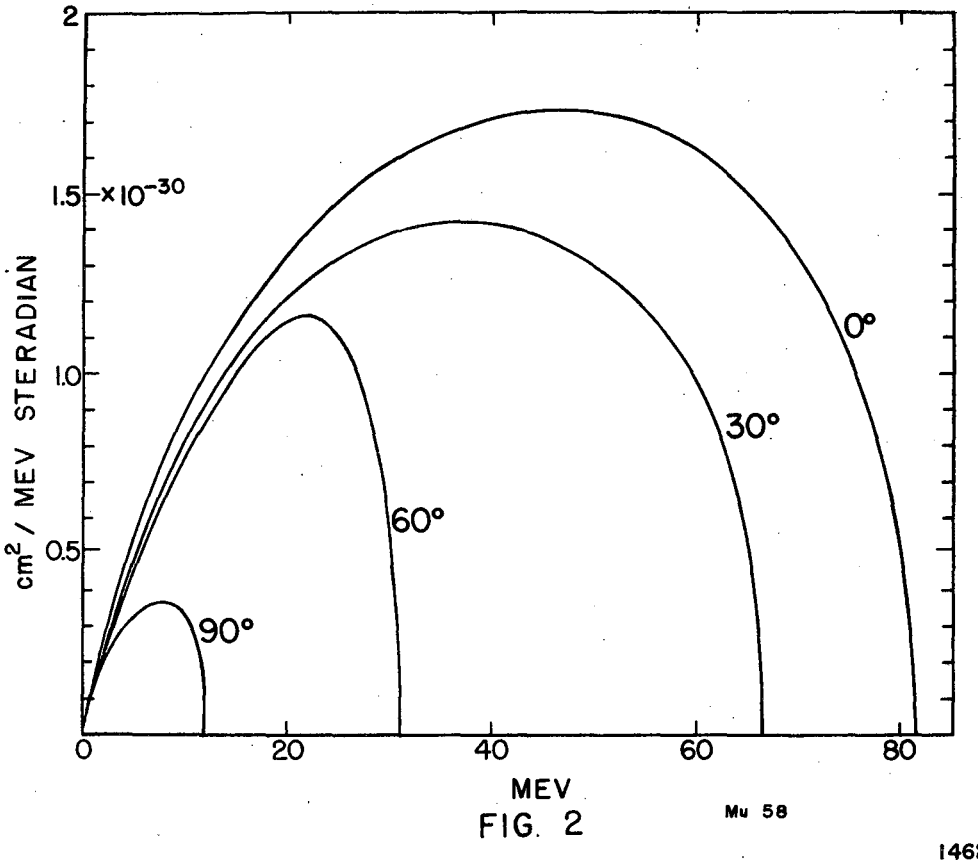

FIG. 2

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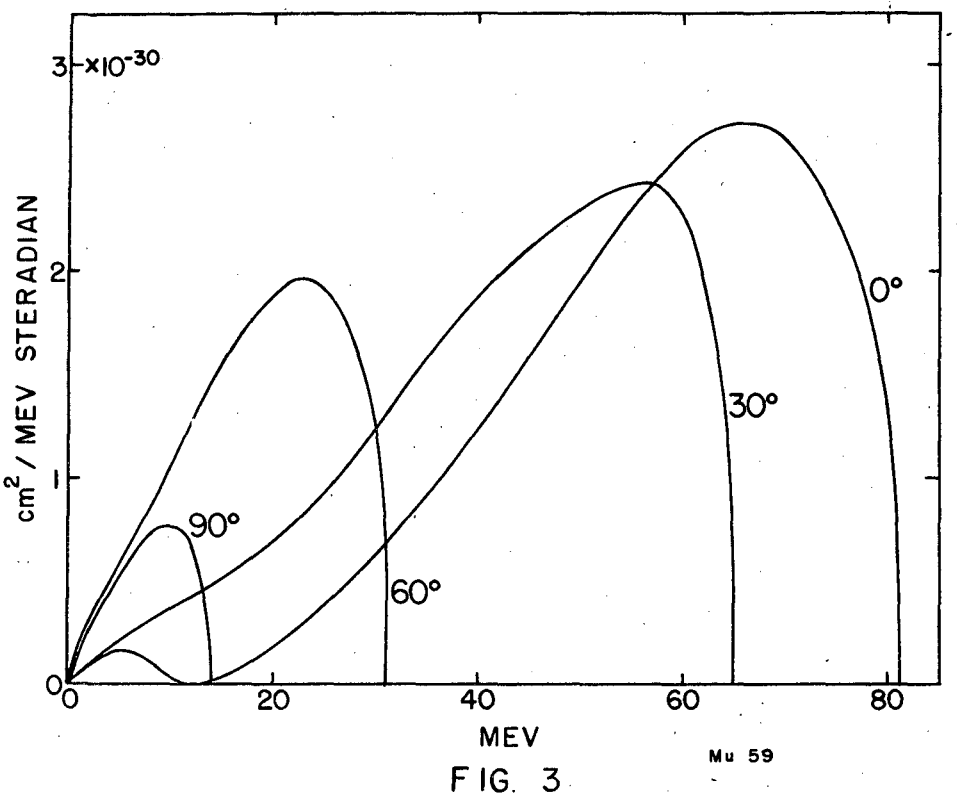

FIG. 3

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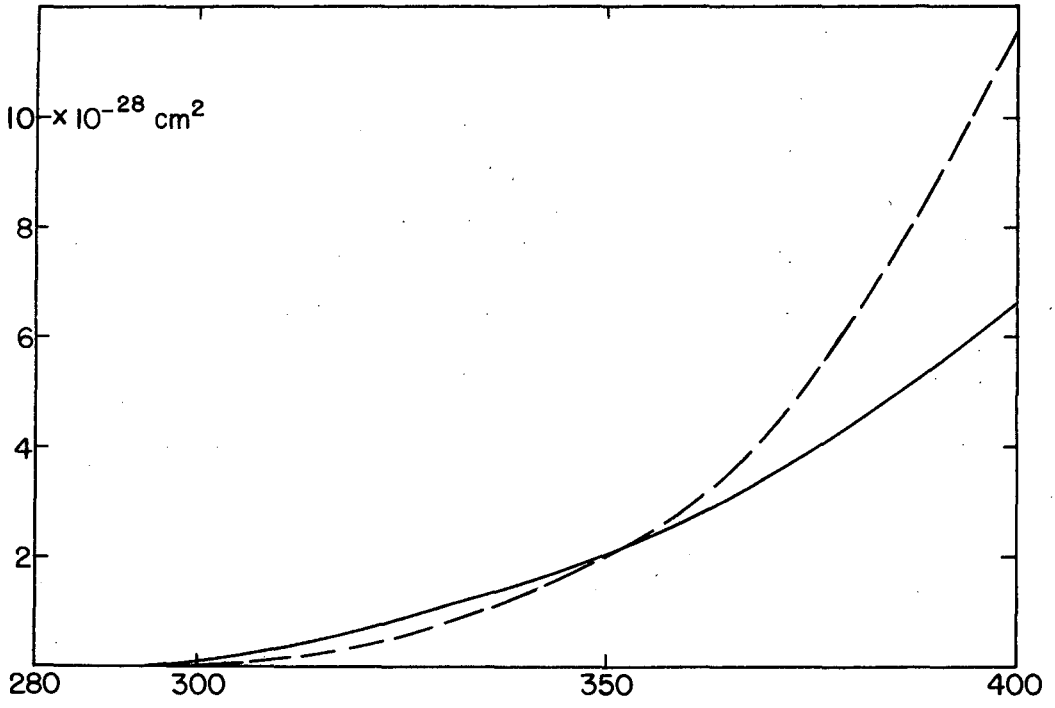

FIG. 4

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