N25 　11ザミ22

01

COLUMBIA UNIVERSITY
BROADWAY AND 120TH STREET, NEW YORK 27, NEW YORK

PHYSICS COLLOQUIUM
7:30 P.M. ROOM 301 PUPIN PHYSICS LABORATORIES

Friday, April 14, 1950

Speaker: Dr. J. R. Haynes
Bell Telephone Laboratories

Subject: The mobility and lifetime of injected holes and electrons in germanium

Friday, April 21, 1950

Speaker: Dr. H. Yukawa

Subject: Present status of meson theory

Friday, April 28, 1950

There will be no Physics Colloquium

(i) General structure of Rel. Theory of Quantized Field.
(ii) Our knowledge about mesons about a year ago (H. Yukawa, Rev. Mod. Phys. 21 (1949), 474)
(iii) Nuclear forces (low energy region, high energy region)
(iv) Neutral mesons
(v) Meson Scattering.
(vi) Creation of mesons
(vii) Remarks on heavier mesons

Present Status of Meson Theory

By Hideki Yukawa

Physics Colloquium, Columbia University
Room 301, Pupin, April 21, 1950

The development of theoretical physics can be regarded in a sense as the development of the concept of "field" contrasted ~~in side by side~~ so in a ~~constant~~ ~~close~~ correlation with that of "matter". We find the best example in the development of electrodynamics. So was the development of meson theory. It started from the extension of the concept of the field of force so as to include the "nuclear forces" in addition to the electromagnetic and gravitational forces.

However, the situation in meson theory was somewhat different from ~~the earlier~~ that in electrodynamics. It ~~Relativity~~ theory was because and quantum theory were there already and they were unified ~~into~~ united together into the theory of "quantized field". In this theory, the ~~most fundament~~ fundamental ~~point was not~~ theme was not so much

field ~~versus~~ and ~~plus~~ matter

as

free fields and interaction between them

In order to make clear this point, I would like to mention very briefly the whole structure of the present theory of quantized field.

(I) Free field
field quantities (operators)
field equations ⇄ commutation relations
spin ⇄ statistics; mass.

(II) Interaction
Schrödinger function or functional
Schrödinger equation
Hamiltonian ~~or~~ Lagrangian
(Operator)
Coupling constants e, g etc.

So far as the free field is concerned, the present theory ~~seems to be~~ is complete by ~~the~~ itself. The requirements of relativity theory ~~of~~ and quantum theory are satisfficient to deduce all possible type of field equations and commutation relations, ~~provided~~ if ~~that~~ we assume further

(i) field equations are linear.
(ii) ~~the~~ particles associated with ~~accompanying~~ the field ~~w~~ are dimensionless particles and obey either ~~the~~ B. E. statistics or F. D. statistics.

However, there is a great arbitraryness as to which ~~of the~~ types of fields are realized in nature. In particular, the values of masses of existing particles must be ~~considered~~ accepted only as such without any fundamental theoretical reason.

As for the interaction, the situation is still worse. ~~It is true that ne One~~ As is well known, the Schrödinger equation for the system consisting of two or more fields interacting with each has no finite solution, so that the present theory of interaction of elementary particles is inconsistent from the beginning. It is true that recent debelopment of ~~f~~ so called many-time-formalism together with the ~~renormali~~ procedure of renormalization of mass and charge (more generally ~~the~~ masses and coupling constants) threw new light on this ~~difficulty~~ problem, but it is certain that ~~it~~ we are still far from the satisfactory solution. Apart from this fundamental difficulty, there is further a great deal of arbitraryness in the choice of the interaction between quantized fields. The only criterion, which was useful, is that the interaction operator must be as simple as possible, as just we postulated that the field equations ~~must be as simple as possible~~ and commutation relations must be as simple as possible.

Under these circumstances, we must admit that the whole theory of elementary particles, particularly meson theory, is provisional at the present stage.

The ~~best~~ that ~~I can tell~~ we can do today is to discriminate between

(i) what we understand about mesons or more generally about elementary particles

(ii) and what we do not understand as clearly as possible.

~~Today We know now~~ It is generally accepted that there are several groups of elementary particles:

group I	II	III*	IV	V
nucleon				
(N, P);	$(e^{\pm}, \nu)$;	$\mu^{\pm}$;	$\pi^{\pm}, \pi^{0}$;	γ

So far as ~~the phenomena up to about~~ we know, the ~~nucleon~~ neutrons and protons constitute a distinct group I, because a nucleon can be created, only if another nucleon is annihilated, or vice versa.

There is no indication of ~~one~~ the creation or annih. a nucleon, which is not accompanied by the annih. or creat of another.

As for the group II and III, existing experimental results could ~~be~~ be understood more easily by ~~assu~~ regarding them as one single group, because, for example, π-μ-decay ~~can be~~ is usually interpreted as

$$\pi^{\pm} \to \mu^{\pm} + \nu \qquad (I)$$

just as the prototype of the ordinary β-decay is

$$N \to P + e^{\pm} + \nu . \qquad (II)$$

In other words, the creation or annihilation of a μ-meson is associated with ~~by~~ that of ~~one~~ a neutrino, just as the creation or annihilation of an electron is associated with that of a neutrino in the case of β-decay. Alternatively, you may say that μ, e, ν are different states of ~~the same~~ one type of elementary particles just as N, P are those of another type.

~~As for π± and π0~~, ~~Among~~ As for the group IV, we must discuss a little more in detail, because the existence and nature of ~~the~~ π±, π0, particularly of the latter were confirmed experimentally only very recently. The most important property of ~~E~~ this group is the ~~st pro~~ possibility of the processes of the type

$$
\left.
\begin{array}{ll}
 & N \rightleftarrows P + \pi^- \\
\text{or} & P \rightleftarrows N + \pi^+ \\
\text{or} & (P ~~N~~ \rightleftarrows P + \pi^0) \\
 & N \rightleftarrows N + \pi^0
\end{array}
\right\} \text{(III)}
$$

As wellknown ~~that~~ this possibility of such processes characterize by ~~with~~ a large coupling constant g ~~was the fundamental assumption of meson~~ has be regarded as the main support of the meson theory.

Of course, such processes cannot ~~occur~~ be observed directly because the laws of conservation of energy and momentum are not satisfied. These processes are combined together into the processes such as

$$
\left.
\begin{array}{l}
N + P \rightarrow P' ~~N~~ + \pi^- + P \rightarrow P + N', \\
~~N~~ P + P' \rightarrow P'' + \pi^0 + P' \rightarrow P' + P'''
\end{array}
\right\} \text{(IV)}
$$

which are supposed to be responsible for the nuclear forces* ~~manifested in the~~ However, it should be noticed that the notion of <u>nuclear forces</u> is not as clear as the notion of

* Discussions of Deuteron problem and N-P, P-P scattering

~~for~~ electrostatic force (Coulomb force), because the simple notion of nuclear static potential cannot be applied to a very short distance of the order of ~~ħ~~/μc between nucleons (and, hence nucleon-nucleon scattering at high energy), whereas Coulomb potential has always the definite meaning, because it appears as the inevitable consequence of the elimination of longitudinal and ~~scalar~~ time components of the electromagnetic potential.

~~We be~~ The creation of a π-meson by collision of a high energy proton or a neutron with ~~the~~ nucleus was certainly ~~regarded~~ as a more direct evidence for (II). However, ~~there remains still various~~ it does not follow necessarily that (IV) is the main contribution to the nuclear forces, as long as the collided nucleus is a complex nucleus such as ~~C~~ carbon, because the interaction between the nucleon and the carbon nucleus might be more complicated and the emission of a π-meson might be the final result ~~a consequence~~ of such various ~~complicated~~ competent ~~pro~~ possible processes.

In this connection, recent experiments in Berkeley concerning the interaction of π-mesons with protons is of decisive importance. In this case, ~~another~~ wellknown ~~type~~ of processes such as

$$P \rightleftarrows P' + \gamma \qquad (\mathrm{IV})$$

~~now~~ is supposed to ~~take~~ participate together ~~with~~ the process (III). Namely, when ~~a negative~~ π^- is absorbed by P, the result must be a simple scattering of the type

$$P + \pi^- \underset{g}{\rightarrow} N \underset{g}{\overset{e(mag.)}{\rightarrow}} P' + \pi^{-\prime}$$

or ~~more precisely~~

$$P + \pi^- \underset{e}{\rightarrow} P' + \gamma + \pi^- \qquad \left(\text{or } P + \pi^- \underset{g}{\rightarrow} N + \pi^+ + \pi^- \underset{e}{\rightarrow} N + \gamma \text{ etc} \right)$$

$$\rightarrow N + \gamma,$$

$$P + \pi^- \gamma \underset{g}{\rightarrow} N \underset{e(mag)}{\rightarrow} P' + \gamma,$$

which is the combination of (IV). It was known that the specific nuclear interaction ~~is too~~ contribute appreciably to the collision between π^- and P, only when π^- is slowed down ~~to~~ and captured into a low Bohr orbit in a time short compared with the mean life-time $\tau_\pi \sim 10^{-8}$ sec. (at least for liquid hydrogen).* ~~a~~ Moreover, the ~~subsequent~~

* R. E. Marshak and A. S. Wightman, Phys. Rev. 76 (1949), 114. Wightman, ibid 77 (1950), 521. See also G. Araki, Sci. Paper 39 (1941), 14.

probability of subsequent absorption of π^- resulting in the emission of γ is much larger than that of the spontaneous decay of π^-. Recently, calculations of this process were made by Marshak and Wightman* for the scalar and pseudo-scalar mesons. They are

$$\tau_S = 8.0 \times 10^{-15}\ \text{sec}. \qquad *$$
$$\tau_P = 1.1 \times 10^{-15}\ \text{sec}.$$

for the absorption from the bound state in liquid hydrogen with

$$g^2/\hbar c = 0.25 \qquad f^2/\hbar c = 0.25.$$

~~At any rate~~ Thus, we expect that ~~a~~ monochromatic γ-rays of energy around μc^2.

Recent experiment by Panofsky** indicates on the contrary the ~~appearance~~ spectrum of γ-rays with the band around 65 MeV and a line at 130 MeV. This could ~~only~~ be understood, only if we assume the existence of π^0 with the mass

$$m_{\pi^0} < m_\pi - (M_N - M_P),$$

---

* $$1/\tau_S = 2\left(e^2/\hbar c\right)^4\left(g^2/\hbar c\right)\left(\Gamma\mu/M\right)^2\left(\bar{\mu}/\mu\right)^2\left(\mu c^2/\hbar\right)$$

Γ : difference of magnetic moments, or $\Gamma = 4.71$

$$1/\tau_P = 8\left(e^2/\hbar c\right)^4\left(f^2/\hbar c\right)\left(\bar{\mu}/\mu\right)^2\left(\mu c^2/\hbar\right)$$

$$\bar{\mu} \doteq \mu M/\mu + M$$

** New York meeting & Private Conversation so that a process of the type

$$P + \pi^- \xrightarrow[g]{} N' \xrightarrow[g]{} N + \pi^0$$

$p + \pi$ $\searrow_g$ ~~N + π~~ $P' + \pi^0 + \pi^-$ $\uparrow g$

$$\pi^0 \rightarrow \gamma + \gamma$$

may occur side by side with the above one quantum process as suggested by Marshak and Wightman. According to them

$$\tau_{SS} \sim 2 \cdot 10^{-15} \left(\frac{p_0}{\mu c}\right) \text{ sec.}$$

$$\tau_{PP} \sim 2 \cdot 10^{-15} \left(\frac{p_0}{\mu c}\right) \text{ sec.} \quad *$$

(See Appendix)

On the other hand, ~~the~~ there is a very strong ~~eviden~~ indication of the 2γ-decay of neutral π-mesons, namely according to measurement of York and others,** in Berkeley, the intensity of high energy γ-rays produced by the collision of high energy protons with various light nuclei such as C and Be increases

** R. Bjorklund, W. E. Crandall, B. J. Moyer and H. F. York, Phys. Rev. 77 (1949), 213.

* $$1/\tau_{SS} = 4\left(\frac{e^2}{\hbar c}\right)^3 \left(g^2/\hbar c\right) (\Delta g^0)^2/\hbar c \left(p_0/\mu c\right)\left(\mu_0/\bar{\mu}_0\right)\left(\bar{\mu}/\mu\right)^3 \left(\mu c^2/\hbar\right)$$

$\Delta g^0 = g^0_N - g^0_P$

$f^0 = \frac{f^0_P + f^0_N}{2}$

$$1/\tau_{PP} = 4\left(e^2/\hbar c\right)^3 \left(f^2/\hbar c\right)\left(f^{0\,2}/\hbar c\right)\left(p_0/\mu c\right)\left(\bar{\mu}/\bar{\mu}_0\right)\left(\bar{\mu}/\mu\right)^2 \left(\mu c^2/\hbar\right)$$

very rapidly, when the energy of the photon becomes larger than the threshold for the production of $\pi^{\pm}$-mesons. ~~Moreover the intensity of~~ For 290 MeV and 340 MeV, the intensity is of the same order of magnitude as the intensity of $\pi^{\pm}$-mesons ~~with~~ and the energy distribution has a maximum around 70 MeV. ~~70 MeV~~ This could be ~~ex~~ accounted for consistently by assuming the 2γ-decay of π^0-~~me~~ mesons, which were produced side by side with $\pi^{\pm}$. They estimated the mass ~~around~~ about $300 m_e$, but their results are not inconsistent with the assumption that the mass m_{π^0} is a little smaller than ~~that of the~~ m_{π}. Moreover, Panofsky and Steinberger (Appendix) carried out the experiment, ~~which~~ confirming the coincidence of two γ-rays due to the 2γ-decay.

Thus the existence of neutral π-mesons, which have been expected ~~from the~~ for long time theoretically, seems to be finally confirmed. Theoretical arguments for postulating the neutron mesons ~~were~~ (sometimes called neutretto)

(i) Approximate charge independence of Nuclear forces

(ii) Interpretation of P-P scattering

F4c

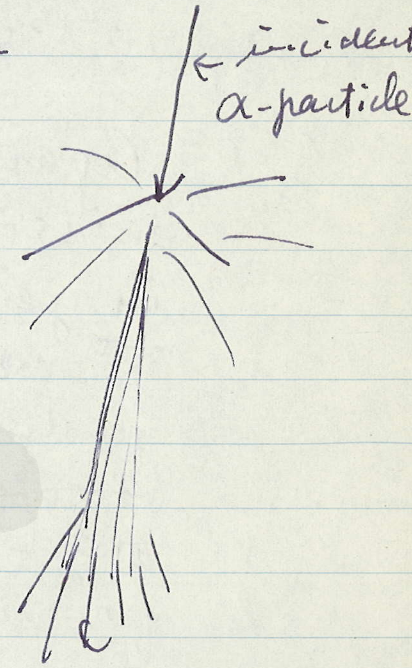
Now the γ-decay of neutral mesons, which was also predicted theoretically years ago, is an interesting subject by itself. It has been known that a scalar or a pseudoscalar mesons can decay into ~~three mes~~ of two photons and the life-time may be of the order of 10^{-14} sec or smaller,* whereas a vector meson or a p.v. meson can decay only into three photons with much long life-time.

Recent some evidence, which support this theoretical argument, was obtain in Rochester in connection with the so-called "R-shower"** in cosmic rays. This is a high energy shower consisting of a narrow dense core of relativistic particles ~~and~~ (23±2 particles) ~~and surrounding~~ surrounded by a more diffuse shower of 33 relativistic particles. In addition 18-non-relativistic particles carrying at 23 units of charge and a total energy of ~3 BeV emerge from the origin of the shower.

** M.F. Kaplon, B. Peters and H.L. Bradt, Phys. Rev. 76 (1949), 1735; R.E. Marshak, ibid. 1736.

* According to recent calculations based on ~~the~~ many-time formalism, the life-time turns out to be 10^{-10} sec for ps. scalar mesons.

Now the most important feature of R-shower is that the number of relativistic particle increases by 11, as we go down along the paths of core particles. In particular, two electron pair of energies ~10 BeV and ~50 BeV were created. Thus, ~~the~~ it seems that the additional particles are electrons ± created by γ-rays in the core. Then, we can conclude that 8 ~ 10 electron pairs are created over an average path length of 0.26 radiation units. This ~~it~~, in turn, implies that the number of γ-rays in the core must be at least 35. (The energy of the primary α-particle is estimated to be about $E_\alpha = 0.8 \times 10^{+13}$ ev, from the angular spread of the core.



The diffuse shower could be accounted for as the result of secondary and tertiary meson production in the same nucleus by some of the nucleons emerging from the primary encounter.) In this way, the above R-shower ~~example~~ could be interpreted as an example of pluro-multiple meson shower on the one hand as first observed by Leprince-Ringuet et al,* and on the other

* L. Leprince-Ringuet et al, C.R. 229 (1949), 1, 163.

hand an evidence for the existence of π^0 meson of $\sim 300\, m_e$ and life-time less than 10^{-13} sec.

Apart from the problem of neutral mesons, existing experimental material indicate in general the strong interaction between $\pi^{\pm}$-mesons and nucleons, which is consistent with the assumption $g^2/\hbar c = 0.1 \sim 1$, ~~However~~ although it is not clear whether $\pi^{\pm}$, π^0-meson are mainly responsible for nuclear forces. The uncertainty comes from the complicated ion of the interaction between nucleons at very short distance ~~between $\hbar/\mu c$ and $\hbar/\mu c$~~ of the order of $\hbar/\mu c$, ~~and a little~~. This might be a deeper question, which is intimately ~~on~~ connected with the question of divergence in general field theory.

However, there is another problem, which is not yet settled down, ~~doubt~~ which does not seem so deep a question. ~~Namely~~, The scattering of $\pi^{\pm}$-mesons by nucleons has been dealed with theoretically from the beginning of meson theory, since it is one of the simplest possible processes. According to conventional perturbation calculations, the cross-section for scalar mesons is*

$$d\sigma_s = \frac{1}{4}\left(\frac{g^2}{Mc}\right)^2\left(\frac{E}{E_0}\right)^2\left\{1+\left(\frac{2Mc^2}{E_0}\right)^2+\frac{E}{E_0}\right\}d\Omega,$$

where E_0, E are the energies of incident and scattered mesons. The total cross-section is

$$\sigma_s = \pi\left(\frac{g^2}{Mc^2}\right)^2\left\{\frac{(2+\gamma)^2}{\gamma^2(1+2\gamma)}+\frac{1+\gamma}{(1+2\gamma)^2}\right\},$$

with $\gamma = E_0/Mc^2$. For $\gamma \sim 1$, σ_s is of the order of 10^{-29} cm^2, so that we can expect ~~that~~ no appreciable contribution to the absorption of $\pi^\pm$ in matter. For $\gamma \ll 1$ (but not too small),

$$\sigma_s = 4\pi\left(\frac{g^2}{E_0}\right)^2 = 4\pi\left(\frac{g^2}{\hbar c}\right)^2\cdot\left(\frac{\hbar c}{E_0}\right)^2$$

$$= 4\pi\left(g^2/\hbar c\right)^2\cdot\left(\hbar/\mu c\right)^2\cdot\left(\mu c^2/E_0\right)^2$$

$$\sim 10^{-26} \sim 10^{-27}\ \text{cm}^2.$$

For pseudoscalar mesons,**

$$d\sigma_{ps} = (\hbar/\mu c)^2(f^2/\hbar c)^2(p_0c/E_0)^2(p_0/\mu c)^2 d\Omega,$$

or

$$\sigma_s = 4\pi(\hbar/\mu c)^2(f^2/\hbar c)^2(p_0c/E_0)^2(p_0/\mu c)^2$$

for $p \sim \mu c$. The ~~first~~ factor $4\pi(\hbar/\mu c)^2(f^2/\hbar c)^2$ again has a value 10^{-26} ~~10^{-27}~~ cm^2.

* H. Yukawa and S. Sakata, Proc. Phys.-Math. Soc. Japan 19 (1937), 1084.

** Y. Tanikawa and H. Yukawa, ibid 23 (1941), 445.

The difference ~~is~~ between ~~ps~~ scalar and pseudoscalar mesons is that the cross-section decreases with the energy E_0 proportional to E_0^{-2} first and then E_0^{-1}, ~~whereas~~ in the former case, whereas it increases with E_0 proportional to ~~p~~ E_0^2. ~~first~~ In any case, the cross-section is always of the order of $10^{-26} \sim 10^{-27}\ \mathrm{cm}^2$ for moderate energies*.

On the contrary, recent experiments by Piccioni** and Fretter*** gave much smaller values for the cross-section. Namely, according to Piccioni for $E_0 \sim 300$ MeV

$$\sigma < 2\times 10^{-27}\ \mathrm{cm}^2 \ (\lambda > 1000\ \mathrm{g/cm}^2)$$

According to Fretter

$$\sigma < 3\times 10^{-28}\ \mathrm{cm}^2 \ (> 15^\circ) \ ~~(\lambda > 750\ \mathrm{g/cm}^2)~~$$

for lead for scattering angle $> 15^\circ$.

---

* ~~Recent~~ according to calculation by R. E. Marshak, Cosmic Rays. Proc. Echo Lake Symposium, 1949 p. 43,

	$E_0 = 1$	$E_0 = 3$
σ_s	$2\cdot 10^{-26}\ \mathrm{cm}^2$	$1\cdot 10^{-27}$
σ_{ps}	$3\cdot 10^{-26}\ \mathrm{cm}^2$	$6\cdot 10^{-27}$

for $g^2/\hbar c \sim 1/4$ $\quad f^2/\hbar c \sim 4$

** O. Piccioni, Phys. Rev. 77 (1950), 1, 6.

*** W. B. Fretter, 76 (1949), 511.

As for the creation of mesons, ~~the present~~ existing experimental data on the nucleon-nucleus collision are not enough to give quantitative conclusion. This is because the ~~collis~~ creation of a meson by collision of a proton or a neutron with a nucleus other than ~~hydro~~ proton is a fairly complicated process.* ~~and~~ Even in the case of the p-p or n-p collision, the processes are more complicated than the corresponding process of creation of a meson by γ-p-collision. For example,

$$P + P' \underset{g}{\rightarrow} N + \pi^+ + P' \underset{g}{\rightarrow} N + \pi^+ + N' + \pi^{+\prime}$$

$$\underset{g}{\rightarrow} P'' + \pi^+ + N' \qquad 1$$

etc

~~or P + P' →~~

$$P + N \underset{g^3}{\rightarrow} N' + N'' + \pi^+ \qquad 1/2$$

$$\underset{g^3}{\rightarrow} P' + P'' + \pi^- \qquad 1/2$$

$$\sigma_{\pi^+}/\sigma_{\pi^-} = 3$$

$$N + N \rightarrow N' + P' + \pi^- \qquad 1$$

$$\sigma_{\pi^+}/\sigma_{\pi^-} = 1/3$$

$$P + P' \rightarrow P'' + P''' + \pi^0 \qquad w_0^{(1)}$$

$$P + N \rightarrow P' + N' + \pi^0 \qquad w_0^{(2)}$$

$$N + N \rightarrow N' + N'' + \pi^0 \qquad w_0^{(3)}$$

* Particularly because the effect of exclusion principle on recoil nucleon.

On the other hand, the process

$$\gamma + P \rightarrow \pi^+ + N$$

for γ-energy of max. $\lesssim$ 330 MeV was investigated recently*, which ~~seems to be~~ is very simple and important for meson theory.

(Paraffin – Carbon) The calculations are performed years ago and recently by Feshbach.**

According to Araki*** the cross-section of production of a pseudoscalar meson by γ-p-reaction is

$$d\Phi_{ps} = 2\Phi_0 \left(\frac{Mc^2}{E_0^2}\right)\left(\frac{E}{E_0} - \xi\right) dE$$

where

$$\xi = 2\left\{\frac{\mu c^2 \cdot p \cdot c \sin\theta}{c\sqrt{(p_0-p_1)^2+\mu^2c^2}+(E_0-E)^2}\right\}^2$$

$$+ \frac{(\mu c^2)^2}{2Mc^2 \cdot E_0} \quad : \text{negligible}$$

$$\Phi_0 = \pi\left(\frac{1}{2}\frac{ef_1}{\mu c^2} + \frac{ef_2}{\mu c^2}\right)^2$$

$$\Phi_{ps} = 4\pi\left(\frac{1}{2}\frac{ef_1}{Mc^2} + \frac{ef_2}{\mu c^2}\right)^2 \frac{(E_0+Mc^2)\{Mc^2E_0+\frac{1}{2}(\mu c^2)^2\}}{E_0(2E_0+Mc^2)^2}$$

$$\times \sqrt{\left(1-\frac{\mu}{2M}\cdot\frac{\mu c^2}{E_0}\right)^2 - \left(\frac{\mu c^2}{E_0}\right)^2}$$

*** G. Araki, Sci. Pap. 39 (1941), 14.
See Appendix.

* J. Steinberger and A. S. Bishop, Berkeley Report.

** H. Feshbach and M. Lax, Phys. Rev. 76 (1949), 134;

For $\mu c^2 < E_0 < Mc^2$

$$\Phi_{ps} \sim 4\Phi_0$$
$$= 4\pi\left(\frac{1}{2}\frac{ef_1}{Mc^2} + \frac{ef_2}{\mu c^2}\right)^2$$
$$\sim 10^{-28} \sim 10^{-29}\,\mathrm{cm}^2$$

The corresponding cross-section for scalar mesons is

$$d\Phi_s = 2\pi\left(\frac{eg_1}{\mu c^2}\right)^2 \frac{Mc^2}{E_0^2}\left[\left\{1-\left(\frac{\mu}{2M}\right)^2\right\}\right\}$$
$$+\left(\frac{\mu}{2M}\right)^2\left(\frac{E}{E_0} - \frac{2Mc^2}{E_0}\right)\Big] dE$$

and

$$\Phi_s \simeq 4\pi\left(\frac{eg_1}{E_0}\right)^2 \log\left(E_0/\mu c^2\right) \quad \text{for } \mu c^2 < E_0 < Mc^2$$

which is a little smaller than Φ_{ps} and decreases with energy E_0.

In both cases, Φ_{ps} and Φ_s decrease with E_0^{-1} for $E_0 \gg Mc^2$.

Another difference between two cases is that ~~the~~ $d\Phi_{ps}$ gives ~~an angul~~ a rather flat angular distribution with the maximum for an angle larger than $90°$, whereas $d\Phi_s$ gives a maximum for ~~the~~ an angle less than $90°$. The experiment is in favour of ~~the~~ the pseudoscalar mesons. (See, however, Appendix)

Finally I would like to add a few ~~conclusion~~ remarks on the problem of heavier mesons.
Theoretically, we can easily conceive that if a type of ~~meson~~ ~~boson~~ mesons heavier than π-meson is created ~~to~~ in cosmic rays ~~in sufficiently large number~~ frequently, this implies that the life-time of such mesons will be very short.
On the contrary, if the life-time is sufficiently long to be observed, they may not be created abundantly.
This is because the probability of creation is proportional to g_τ^2, whereas the life-time is proportional to g_τ^{-2}.
Under these circumstances, we can ~~say~~ not expect a large percentage of heavier mesons in cosmic rays, but still we cannot exclude the existence of them. Recent experiment by Anderson ~~might b con~~ (and ~~other~~ previous experiments on τ-mesons) could be understand in this way.

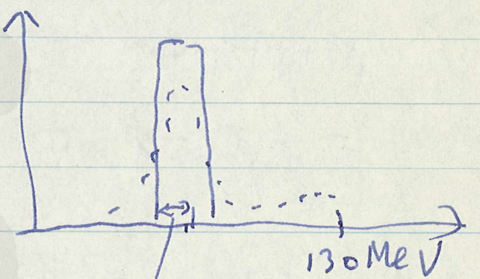
Appendix to
"Present Status of Meson Theory"

On Neutral Mesons. April 11, 1950

W. Panofsky, π^--P-reaction
(New York meeting, Private talk)

L. Aamodt,
H. York

130	1.35
85	4.
60	13.
40	6



$\pi^- + P \to \pi^0 + N \to \gamma + \gamma + N.$
$\searrow \gamma + N$

(π^- + He : no γ-ray)

$$\frac{A_\pi}{A_\gamma} \cong \frac{g^2}{e^2} \cdot \frac{p_{\pi^0}}{\mu c}$$

$0.1 < g^2/\hbar c$

? ~~1.5 MeV~~ $\Delta M <$ Δ ~~[illegible]~~ μ $<$ ~~2.9 MeV.~~

1.3 MeV $\leq \Delta\mu <$ 4.7 MeV

$M_N - M_P < m_\pi - m_{\pi^{(0)}}$

S. Hayakawa, ~~Letter~~ Priv. Comm.

π, π^0: scalar neutral theory:

$A_\pi \gg A_\gamma$

~~pseudo~~ scalar, symmetrical theory:

$A_\pi \ll A_\gamma$

pseudoscalar symmetrical

$A_\pi \sim A_\gamma$.

Marshak, Washington Meeting

(Panofsky ?)

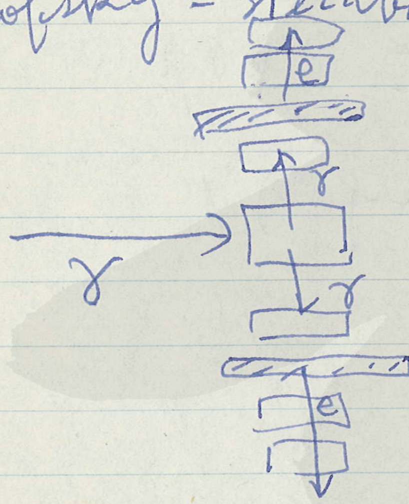
$P + P \to \pi^0$ $\qquad \frac{\sigma_H}{\sigma_C} < 0.02$? energy threshold

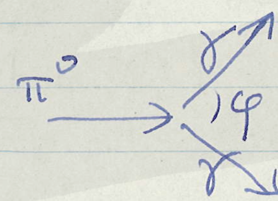
$P + C \to \pi^0$

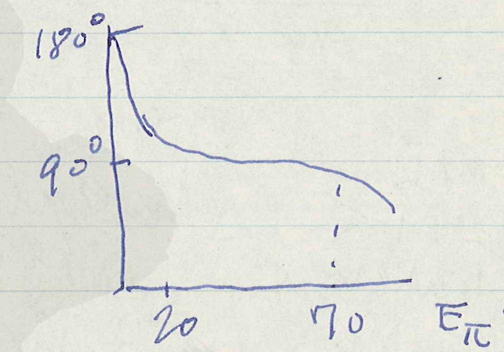
$\gamma + P \to \pi^0$ $\qquad \frac{\sigma_H}{\sigma_C} < 0.1$

$\gamma + C \to \pi^0$

Panofsky - Steinberger







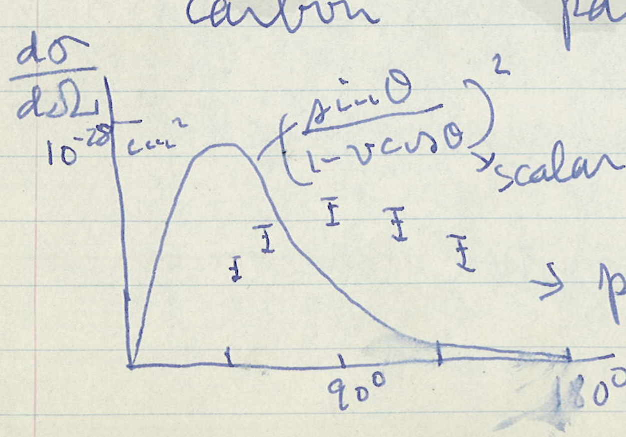
Steinberger and Bishop, New York Meeting 1950

$\gamma + P \to N + \pi^+$ $\qquad \frac{\sigma_H}{\sigma_C} > \frac{1}{12}$

$\gamma + C \to B + \pi^+$

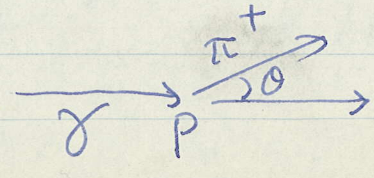
Physical Rev. 78 (1950), 494.

carbon paraffin



$h\nu = 250$ MeV

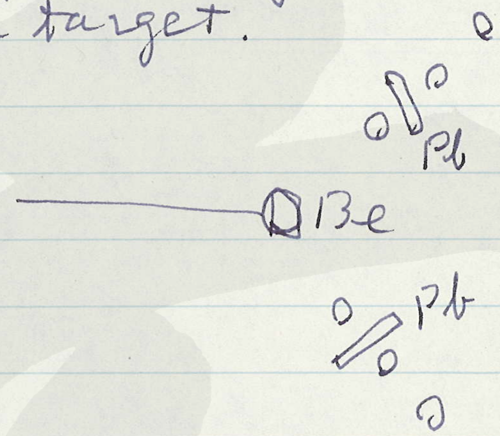
$\gamma + P \to \pi^+ + N$



Evidence for the Production of Neutral Mesons by Photons

by J. Steinberger, W. K. H. Panofsky and J. Steller.

Synchrotron X-rays of 330 MeV maximum energy strike a target of Be. Simultaneous pulses (resolving time 10^{-7} sec.) are recorded in the outer four crystals, but none in two near the target.



$$\sigma_{H,\pi^0} / \sigma_{C,\pi^0} = 0.12 \pm 0.03$$

$$\sigma_{H\pi^+} / \sigma_{C\pi^+} \cong 0.55$$

This might be due partly to the fact that only protons contribute to π^+ production and ~~that~~ partly to the exclusion principle, which is more effective for $\sigma_{C\pi^+}$ than for $\sigma_{C\pi^0}$

$$\sigma_{Be} = 7.5 \times 10^{-28}\ cm^2$$

$$\sigma_C = 10 \times 10^{-28}$$

$$\sigma_H = 1.3 \times 10^{-28}$$

Hydrogen cross-section is approximately the same as that for π^+ production, these for Carbon and Beryllium are somewhat longer.

R. E. Marshak and A. S. Whitman, ~~P~~ Bull. Washington Meeting, April 1950.

width of pulse $w = 35 \pm 15$ MeV

ratio of heights of pulse and line $h = 10 \pm 2$ %

$\mu_0 c^2 = 135 \pm {}^{2}_{5}$ MeV

Ps. sc. $g^2/\hbar c = 0.55 {}^{+0.3}_{-0.1}$

sc. $g^2/\hbar c = 0.07 {}^{+0.04}_{-0.01}$

ps. sc π^0 sc. π^- } forbidden.
sc. π^0 ps. sc. π^-

relative sign of coupling of π^0 with neutron and proton.

Seriff, Leighton, Hsiao, Cowan and Anderson, Thirty-four "forked tracks" similar to Rochester and Butler, Nature 160 (1947), 855.

unstable neutral particles with life $(3 \pm 2) \times 10^{-10}$ sec.

unstable charged particles with a little shorter life

30% of penetrating particles

two charged ~~particles~~ secondaries of unstables particles, ~~have~~ one has a mass 150 me ~ 350 me.

One has a strong nuclear interaction

γ-decay of neutral mesons

$\pi^0 \underset{g}{\rightarrow} P + (\bar{P}') \underset{e}{\rightarrow} P'' + \gamma + (\bar{P}') \underset{e}{\rightarrow} \gamma + \gamma'$

$\underset{e}{\rightarrow} P + \gamma + (\bar{P}'') \underset{e}{\rightarrow} \gamma + \gamma'$

$\left(\frac{\mu c^2}{\hbar}\right)\left(\frac{g^2}{\hbar c}\right)\cdot\left(\frac{e^2}{\hbar c}\right)^2$

$\sim 10^{+23}\ 10^{-1}\cdot 10^{-4} \sim 10^{+18}$

Selection rule:

C. N. Yang, Phys. Rev. 77 (1950), 242, 722

Relativistic Calculations on
γ-P → N-π⁺-reaction

Z. Koba, T. Kotani and S. Nakai,
Prog. Theor. Phys. 5 (1950), 137.

ps. scalar theory:

$\sigma_- = 2.0\left(\frac{e^2}{\hbar c}\right)\left(f^2/\hbar c\right)\left(\hbar/\mu c\right)^2 \times 10^{-2}$

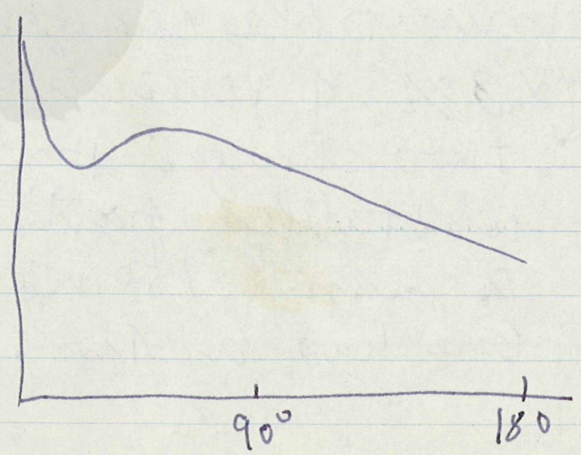
$\sigma_+ = 1.5$ ″

for energy of γ-ray $= 2\mu c^2$

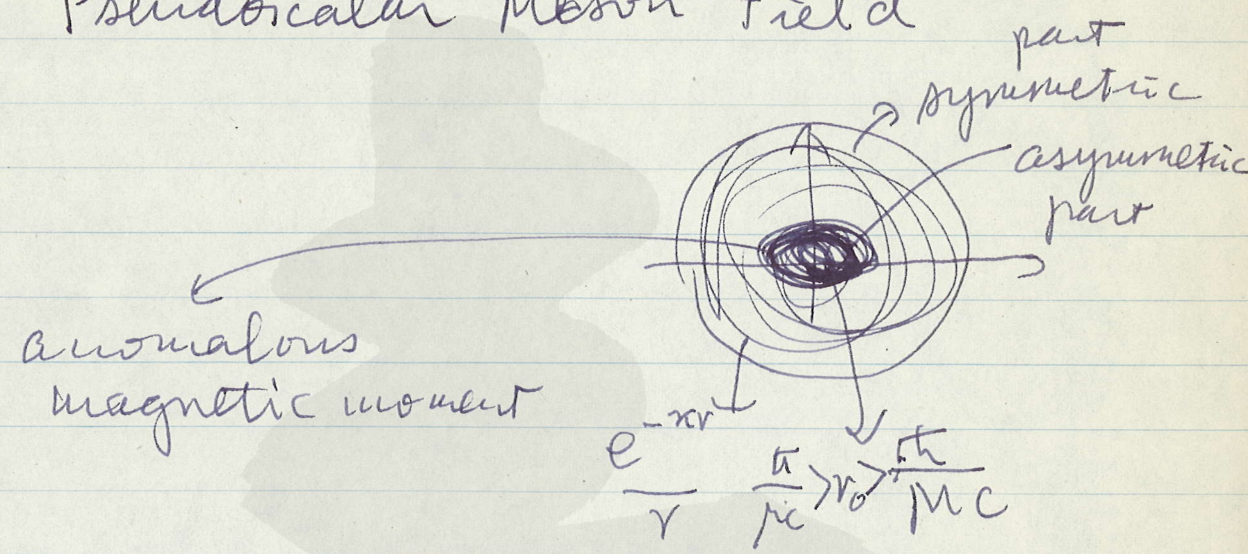
$\sigma_-/\sigma_+ = 1.4$

For $f^2/\hbar c \sim 0.1$ $\sigma \sim 10^{-29}\ \mathrm{cm}^2$

Scalar theory
$\sin^2\theta$-distribution
near threshold



Nuclear Potential in Pseudoscalar Meson Field



K. A. Brueckner
Production of Mesons by Photons
(UCRL-597)

16

Feshbach and Lax, Phys. Rev. 76 (1949), 134.
Foldy, ibid. 372
Brueckner and Goldberger, ibid. 1725.

$$\frac{\sigma_{p+}}{\sigma_-} = \left(\frac{e \frac{\vec{v}_\mu \vec{A}}{1-\frac{v_\mu}{c}\cos\Theta_\mu}}{-e\frac{\vec{v}_\mu \vec{A}}{1-\frac{v_\mu}{c}\cos\Theta_\mu} + e\frac{\vec{v}_M \vec{A}}{1-\frac{v_M}{c}\cos\Theta_M}} \right)^2$$

$$= \left[1 - \frac{q_0}{Mc^2}\left(1-\frac{v_\mu}{c}\cos\Theta_\mu\right)\right]^2$$

q_0: meson energy $= \frac{\mu c^2}{\sqrt{1-v_\mu^2/c^2}}$

Θ_μ: angle between meson and photon

effect of magnetic moments.

$$\frac{\sigma_+}{\sigma_-} = \left(1 - \frac{\gamma_p - \gamma_N}{\gamma_p + \gamma_N}\frac{q_0}{Mc^2}\left(1-\frac{v_\mu}{c}\cos\Theta_\mu\right)\right)^2$$

$$= \left[1 - .20\,\frac{q_0}{Mc^2}\left(1-\frac{v_\mu}{c}\cos\Theta_\mu\right)\right]^2$$

Angular distribution $\frac{1}{(1-\beta\cos\Theta)^2}$ is inclined to the forward direction for $\beta \sim \beta_\mu$ and near symmetric with respect to $90°$ for $\beta \sim \beta_M$.

A. Scalar Meson

predominance of $\mu \cdot \gamma$ (electric dipole) interaction.

B. Pseudoscalar Meson

Roughly isotropic distribution due to magnetic moment of the nucleon coupled to the photon. This is because the electric dipole interaction between the meson and the photon is small, the mesons are strongly bound to a distance small compared with $\hbar/\mu c$.

Preliminary experimental results indicate that the spectrum of mesons observed is roughly isotropic.

Vector and Pseudovector mesons show a strong asymmetry in angular distribution

Stationary State of Two Nucleon System in Rel. Theory.

$$H\Psi = E\Psi \qquad H = H_1 + H_2 + H_{12}$$

$$\Psi(r_1, \sigma_3^{(1)} \rho_3^{(1)} ; r^{(2)} \sigma_3^{(2)} \rho_3^{(2)} ; n_k)$$

$$H_1 = -c\alpha p + Mc^2\beta$$

$$H_2 = \sum_k n_k k_0 \hbar c$$

$$H_{12} = \sqrt{4\pi} f_1 (\rho_2^{(1)} U(r_1) + \rho_2^{(2)} U(r_2))$$

$$+ \sqrt{4\pi} f_2/\kappa \{ \sigma^{(1)} \text{grad}\, U(r_1)$$

$$+ \sigma^{(2)} \text{grad}\, U(r_2) + c\rho_1^{(1)} U^+(r_1) + c\rho_1^{(2)} U^+(r_2) \}$$

$$+ \frac{1}{2} \left(\frac{f_2}{\kappa}\right)^2 2 \rho_1^{(1)} \rho_1^{(2)} \delta(r_1 - r_2)$$

$$\gamma^1\gamma^2\gamma^3\gamma^4 \begin{pmatrix} \gamma^1 \\ \gamma^2 \\ \gamma^3 \\ \gamma^4 \end{pmatrix} = \begin{pmatrix} -\gamma^2\gamma^3\gamma^4 \\ +\gamma^1\gamma^3\gamma^4 \\ -\gamma^1\gamma^2\gamma^4 \\ \gamma^1\gamma^2\gamma^3 \end{pmatrix}$$

$$= -\begin{pmatrix} \gamma^2\gamma^3\gamma^4 \\ -\gamma^1\gamma^3\gamma^4 \\ \gamma^1\gamma^2\gamma^4 \\ -\gamma^1\gamma^2\gamma^3 \end{pmatrix}$$

Nuclear Forces, continued.
Effect of High Order Processes
Strong Coupling Theory
Extended Source

18

Scattering of Mesons
by Nucleons

Production of Mesons by
Nucleon - Nucleon Collision

Nuclear β-Decay and μ-ρ-Decay