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中性的 τ^0 介子的衰變*

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中性的 π^0 介子的存在現在已經爲人所公認。羅切斯脫和勃脫勒二氏在一九四七年發現的帶電荷的 τ^+（或 τ^-）介子和中性的 τ^0 介子的存在最近也由安得遜氏及其合作者提供了新的證據。π^0 介子在衰變時放出二個光子，但是 τ^0 介子在衰變時却放出二個帶電荷的質點。因此 τ^0 介子和 π^0 介子是否具有同樣的性質，便成爲一個有興趣的問題。

本文對這一問題做了一個簡短的研究。第一步討論了 τ^0 介子是一個複合質點的可能性。第二步討論了 τ^0 介子是一個沒有自旋的基本質點的可能性。最後討論了 τ^0 介子是一個自旋等於 $\hbar$ 的基本質點的可能性。討論的結果指出：τ^0 介子是一個複合質點的可能性甚小。假使 τ^0 介子是一個沒有自旋的基本質點，牠不會是在核子碰撞中直接產生出來的產物而是間接的衰變產物。假使牠是一個從核子碰撞中直接產生的產物，則其自旋可能等於 $\hbar$。

一．實驗結果的摘要

爲了便於討論，先將有關 τ^0 介子和 π^0 介子的實驗結果摘述如下：

a）根據勃格萊實驗室提供的材料，π^0 介子的質量是 $261 \pm 3\ m_e$。m_e 是電子的質量。當以 350 Mev. 的質子作核子碰撞時 π^0 介子的產生截面與帶電荷的 π^+ 或 π^- 介子的產生截面大約相等。

b）根據勃力斯多爾大學提供的材料 π^0 介子衰變爲二個光子，其半壽命是 3×10^{-14} sec.

c）在穿透簇射中產生的 τ^0 介子的數量約爲有電離能力的質點的數量的 3%。

d）τ^0 介子在衰變時產生二個帶電荷的質點。是否在同時也有中性的質點放出則現在還沒有確定。τ^0 介子的平均壽命是 $3 \pm 2 \times 10^{-10}$ sec.。

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e) τ^0 介子的質量 $\geqq 800\,m_e$。 但是假使在牠衰變時沒有中性的質點產生，那末 τ^0 介子質量的數值不能假定祇有一個。

f) 有些 τ^0 介子衰變時產物和核子間有很强的相互作用。 那些產物的質量在 $150\,m_e$ 和 $350\,m_e$ 之間。

二. τ^0 介子是一個複合質點的假定

因爲 τ^0 介子衰變時產生的帶電荷的質點一方面和核子有很强的相互作用，另一方面其質量又在 $150\,m_e$ 和 $350\,m_e$ 之間，所以很容易使人想到 τ^0 介子可能是一個複合質點。 例如：牠可能由一個帶正電荷的 π^+ 介子和一個帶負電荷的 π^- 介子相互結合而成，或者可能是由一個質子和一個 π^- 介子結合而成。 但是，假使這個假定被接受，我們便很難解釋爲什麼 τ^0 介子的平均壽命有 3×10^{-10} sec. 這樣長。 爲了將這困難具體地顯示出來，我們假定 τ^0 介子是由一個 π^+ 介子和一個 π^- 介子結合而成的複合質點而作一些具體的討論。

根據安得遜氏及其合作者的研究結果，假使 τ^0 介子是由二個帶電荷的 π 介子結合而成，那末 τ^0 介子的質量要比二個帶電荷的 π 介子的質量的總和還要大 $250\,m_e$。 τ^0 介子的衰變現在應該當作類似 α 衰變看而不應該作爲類似 β 衰變看。 在衰變的過程中，每一個帶電荷的 π 介子得到相當於 $125\,m_e$ 的動能。 因爲這二個動能如此大的 π 介子不立卽分離而相互結合達 3×10^{-10} sec. 之久，所以在他們間的相互作用一定有很高和很厚的勢壘。 今假定這勢壘爲長方形，以 V 代表壘高，b 代表壘厚，那末 τ^0 介子的平均壽命的數量級應爲

$$\tau_{\tau^0} \cong \frac{r}{v}\, e^{\frac{2b}{\hbar c}\sqrt{2\,m_\pi(V-E)}} \tag{1}$$

其中

E: 是帶電荷的 π 介子在放出後的動能。

m_π: 帶電荷的 π 介子的質量。

r: 勢壘的內徑。

v: 帶電荷的 π 介子放出後的速率。

設 $m_\pi = 276\,m_e$, $r = \frac{\hbar c}{m_\pi}$, $\tau_{\tau_0} = 3\times10^{-10}$ sec.， 則

$$\frac{b}{\hbar c}\sqrt{m_\pi(V-E)} = 11.1 \tag{2}$$

甚至勢壘之高達 200 Mev. 時，壘寬仍大於核子力範圍十餘倍。這個結論是和事實不符合的。因爲這結論不僅說二個帶電荷的 π 介子之間的相互作用很强，而且說這個作用的範圍遠比核子力的範圍爲大。帶電荷的 π 介子間的散射截面必定很大。在二個核子相碰撞時，每個核子都可以被當作一個四周圍繞着一羣虛介子的質點。π 介子間的散射截面既然很大，核子間的散射截面因之也必然要比實驗觀察所得者爲大。

假使二個帶電荷的 π 介子間相互作用的範圍和核子力的範圍一樣大，那末勢壘的高必須高於 10^4 Mev.。這大約相當於 m_π 的一百倍。在這樣鉅大的相互作用中各種不同的質點將不斷地被產生和消滅，因此將 τ^0 介子僅作爲二個帶電荷的 π 介子結合而成的複合質點這一看法是很成問題的。費米和楊振寧二氏曾經提議，所有的介子都由核子和反核子相結合而成的。爲了解釋 π 介子的質量的數值，他們必須假定核子間相互作用的强度有 2.46×10^4 Mev.，範圍和核子的康普登波長相等。但是他們的理論在目前還祇是一個計劃，在最近的將來不會提供可靠的具體的數字結果。所以現在用他們的理論來討論 τ^0 介子的衰變是過早了一些。別類將 τ^0 介子作爲複合質點的看法也遭遇到同樣的困難。

三. τ^0 介子是一個沒有自旋的基本質點的假定

π^0 介子以 3×10^{-14} sec. 的平均壽命裏衰變爲二個光子這一事實有力地證明了 π^0 介子是沒有自旋的。因爲自旋等於 $\hbar$ 的基本質點不可能衰變爲二個光子。斯坦因倍葛氏用正規化方法計算了各種介子的平均壽命。他所得的中性標介子和準標介子衰變爲二個光子的平均壽命如下：

a) 標介子，標耦合。

$$\tau\,(S.\,S.) = 18 \cdot \frac{(2\pi\hbar c)^3}{g^2 e^4} \cdot \left(\frac{M}{\mu}\right)^2 \cdot \frac{\hbar}{\mu} \tag{3}$$

b) 標介子，矢耦合。

不能衰變成爲二個光子

c) 準標介子，準標耦合。

$$\tau\,(PS.\,PS.) = 8 \cdot \frac{(2\pi\hbar c)^3}{g^2 e^4} \cdot \left(\frac{M}{\mu}\right)^2 \cdot \frac{\hbar}{\mu} \tag{4}$$

d) 準標介子，準矢耦合。

$$\tau\,(PS.\,PV.) = 72\cdot\frac{(2\pi\hbar c)^3}{f^2\,e^4}\cdot\left(\frac{M}{\mu}\right)^4\cdot\frac{\hbar}{\mu} \tag{5}$$

其中:

g, f: 是核子和介子間的耦合常數,

M: 核子的質量,

μ: 中性介子的質量,

e: 電子的電荷。

以 π^0 介子的質量之值代入其中, 我們得到下列各種不同耦合的 π^0 介子的平均壽命。

$$\begin{aligned}
\tau_{\pi^0}\,(S.\,S.) &= 2\times 10^{-14}\,\frac{\hbar c}{g_{\pi^0}^2}\ \text{sec.}\\
\tau_{\pi^0}\,(PS.\,PS.) &= 0.9\times 10^{-14}\,\frac{\hbar c}{g_{\pi^0}^2}\ \text{sec.}\\
\tau_{\pi^0}\,(PS.\,PV.) &= 4\times 10^{-12}\,\frac{\hbar c}{f_{\pi^0}^2}\ \text{sec.}
\end{aligned} \tag{6}$$

$\frac{\hbar c}{g_{\pi^0}^2}$ 和 $\frac{\hbar c}{f_{\pi^0}^2}$ 的數量級是一。 假使我們假定 π^0 介子是一個具有標耦合和矢耦合的標介子或一個具有準標耦合和準矢耦合的準標介子, 斯坦因倍葛氏計算的結果便和實驗的結果很符合。

今 τ^0 介子不衰變爲二個光子而以 3×10^{-10} sec. 的平均壽命衰變爲帶電荷的質點。 假使 τ^0 介子祇能衰變爲二個光子, 則可知其平均壽命必大於 3×10^{-10} sec. 故:

$$\frac{\tau_{\tau^0}}{\tau_{\pi^0}} > 10^4 \tag{7}$$

假定 τ^0 介子之質量爲 π^0 介子之三倍, 則用各種不同的耦合計算所得的 τ^0 介子和 π^0 介子平均壽命間的比例 $\frac{\tau_{\tau^0}}{\tau_{\pi^0}}$ 如下表。

表一 用不同耦合計算得之比例 $\frac{\tau_{\tau^0}}{\tau_{\pi^0}}$

τ^0 介子之種類及耦合 ╲ π^0 介子之種類及耦合	標介子 標耦合	準標介子 準標耦合	準標介子 準矢耦合
標介子 標耦合	$3.7\times10^{-2}\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$1.6\times10^{-2}\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$8.1\times10^{-1}\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$
準標介子 準標耦合	$8.3\times10^{-2}\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$3.7\times10^{-2}\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$1.8\left(\frac{g_{\pi^0}}{f_{\tau^0}}\right)^2$
準標介子 準矢耦合	$1.9\times10^{-4}\left(\frac{f_{\pi^0}}{g_{\tau^0}}\right)^2$	$8.4\times10^{-5}\left(\frac{f_{\pi^0}}{g_{\tau^0}}\right)^2$	$4.1\times10^{-3}\left(\frac{f_{\pi^0}}{f_{\tau^0}}\right)^2$

其中指數 τ^0 或 π^0 是用來標明某數量是屬於 τ^0 介子或 π^0 介子的。從上表和 (7) 可知。

$$\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2, \left[\text{或}\left(\frac{g_{\pi^0}}{f_{\tau^0}}\right)^2, \left(\frac{f_{\pi^0}}{f_{\tau^0}}\right)^2, \left(\frac{f_{\pi^0}}{g_{\tau^0}}\right)^2\right] \geqq 10^4 \tag{8}$$

用 (8) 中耦合常數的比例極難解釋在穿透簇射中產生的 π 介子和 τ^0 介子數目間的比例。根據安得遜氏及其合作者的實驗，在穿透簇射中 τ^0 介子的數目約爲其中有電離能力的質點的數目的 3%。在這些有電離能力的質點中有些可能是質子，不可能全部都是帶電荷的 π 介子。所以帶電荷的 π 介子的數量和 τ^0 介子的數量間的比例的最高限該等於 30 左右。假使在穿透簇射中產生的 π^0 介子的數量和帶電荷的介子的數量相等，則 π^0 介子和 τ^0 介子的數量的比例

$$\frac{N_{\pi^0}}{N_{\tau^0}} \leqq 30 \tag{9}$$

在另一方面我們預計這個比例的第一近眞值應約爲 $\frac{N_{\pi^0}}{N_{\tau^0}} \simeq \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2 > 10^4$。

要將在核子碰撞時的介子產生截面作一準確的估計是很困難的。 直到現在我們還沒有處理介子輻射反作用完滿的理論。 甚至一共有幾種介子和核子間有較强的相互作用，核子力主要由那幾種介子產生也不清楚。但是將影響核子碰撞時產生介子的截面的各個因素加以討論仍然是有用的。

核子碰撞時產生中性介子這一現象和一個介子在庫倫電場中產生轫致輻射相類似。其第一近眞矩方陣素由二個因子組織。這二個因子可以當作下列的二個變化步驟看:

a）核子發射一個中性介子，

b）核子間動量經過相互作用彼此傳遞。

第一個因子和耦合常數 g_{π^0} 或 g_{τ^0} 成正比。第二個因子由 U 的傅立葉成分決定。不論發射 τ^0 介子或 π^0 介子的時候，祇要傳遞的動量相等，第二個因子的大小也應該大約相等。 假使不計及矩方陣素和碰撞核子的動能之間的詳細關係，則在穿透簇射中 $\frac{N_{\pi^0}}{N_{\tau^0}}$ 之數值應大約與 $\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$ 相等。

在另一方面，τ^0 介子的質量比 π^0 介子的質量重三倍以上。 所以可供產生 π^0 介子用的動量空間較可供 τ^0 介子產生者爲大。同時，宇宙射線中核子的譜和 $\frac{1}{E^{2.5}}$ 成比例，E 是核子的能。 所以核子的數量隨着核子的能而減少。 在核子能譜的下截中有一段可以產生 π^0 介子，但是不可能產生 τ^0 介子。 最後 $\frac{g^2_{\pi^0}}{\hbar c}$ 的數量級是一，同時產生幾個 π^0 介子的可能性很大。 假如 g_{τ^0} 像 (8) 中所指出的那樣小，則同時產生幾個 τ^0 介子幾爲不可能。 所有這些因素都利於產生 π^0 介子而不利於產生 τ^0 介子，使

$$\frac{N_{\pi^0}}{N_{\tau^0}} > \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2 \tag{10}$$

當然，可能因爲 π^0 介子和 τ^0 介子對於核子的耦合方式不同，在核子的動能增高的時候，τ^0 介子產生截面相對的增加了。 但是因爲核子的動能愈高，核子的數目愈少，所以這一個因素不可能起決定性的作用。

由此看來，(8) (9) 和 (10) 間的衝突是很難解決的。假使 g_{τ^0} 眞如 (8) 中所指出的那樣小，那末在穿透簇射中 τ^0 介子的數量要比實際觀察到的要小得很多。 這現象唯一可能的解釋是 τ^0 介子並不是在核子碰撞中直接產生的。 τ^0 介子和核子間並沒有直接的相互作用。 所以 τ^0 介子經由虛核子偶而衰變的可

能性便很小。根據本節的討論，可知假使 τ^0 介子沒有自旋，那末牠是一個比牠更重的核子碰撞中直接產生的質點的衰變產物。

四. τ^0 介子是一個自旋等於 $\hbar$ 的基本質點的假定

根據角動量守恆定律，矢介子和準矢介子不能衰變爲二個光子。斯坦因倍葛氏的計算指出準矢介子甚至不可能衰變成爲三個光子。矢介子衰變爲三個光子的可能性是和 e^6 成正比例的。所以自然比和 e^4 成正比的標介子和準標介子衰變爲二個光子的可能性爲小。斯坦因倍葛氏計算所得中性矢耦合的矢介子衰變爲三個光子的平均壽命公式如下：

$$\tau\,(V.\,V.) \cong 200 \cdot \frac{(2\,\pi\,\hbar\,c)^4}{g^2\,e^6} \cdot \left(\frac{M}{\mu}\right)^8 \cdot \frac{\hbar}{\mu} \qquad (11)$$

張耦合的矢介子的平均壽命的數量級和上式相類。所以矢 τ^0 介子和準標耦合準標 π^0 介子平均壽命間的比例是：

$$\frac{\tau_{\tau^0}}{\tau_{\pi^0}} \cong 25 \cdot \frac{2\,\pi\,\hbar\,c}{e^2} \cdot \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2 \cdot \frac{\mu_{\pi^0}^3\,M^6}{\mu_{\tau^0}^9} = 1.3 \times 10^5 \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2 \qquad (12)$$

根據 (7) 這比例得比 10^4 大。所以從 (12) 得出 $\left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$ 的值和 (10) 沒有矛盾。由此可知，假使 τ^0 介子直接在核子碰撞中產生，則其自旋可能等於 $\hbar$。

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THE DECAY OF THE NEUTRAL τ^o-MESON*

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Abstract

A comparison between the decay phenomena of the neutral τ^o- and π^o-mesons is made. The possibilities of the neutral τ^o-meson's being a particle of spin zero or $\hbar$, or being a composite particle are discussed.

The existence of the neutral π^o-meson is now well established, while the existence of the charged τ^+-(or τ^--) meson and neutral τ^o-meson reported by Rochester and Butler has recently received new confirmations from Anderson and his co-workers. The fact that the π^o-meson decays into photons on the one hand and the τ^o-meson decays into charged particles on the other, raises the question, whether these two kinds of mesons are of the same transformation property.

This note makes a short investigation into the problem and suggests: The τ^o-meson should be a secondary decay product of some still heavier particle produced in a nuclear collision, if it were of spin zero. It might have a spin $\hbar$, if it were created directly during a nuclear collision. The possibility of the τ^o-meson's being a composite particle of one π^+-meson and one π^--meson bound together is also discussed.

1. THE SUMMARY OF EXPERIMENTAL RESULTS

It is convenient to give here a brief summary of the experimental facts about the π^o- and τ^o-mesons.[1-5]

*Contributions from the Institute of Modern Physics, Academia Sinica, Series A, No. 6.

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a) According to the evidence from Berkeley, the π^0-meson has a mass of $261 \pm 3\ m_e$ (electronic mass). The cross-section for its production at 350 Mev. incident proton energy is comparable with that of the π^+- or π^--meson.

b) The π^0-meson decays into two photons. The half lifetime given by the Bristol group is 3×10^{-14} sec.

c) The number of τ^0-mesons created in the penetrating shower is about 3% of that of the ionizing particles produced.

d) Two charged particles are created during the decay of the τ^0-meson. It is not certain, whether neutral particle is also produced during the process. The mean lifetime of the τ^0-meson is $3 \pm 2 \times 10^{-10}$ sec.

e) The mass of the τ^0-meson is roughly 800 m_e or larger. However, there is difficulty in assuming a single mass value for the τ^0-mesons, if it is assumed that no neutral particle is emitted during the decay process.

f) Some of the secondary particles produced in the decay of the τ^0-meson have strong interaction with nucleons. In one case, the track of one secondary particle was unusually long and of high curvature, from which it is estimated, that the mass of this secondary particle is between 150 m_e and 350 m_e.

2. THE τ^0-MESON AS A COMPOSITE PARTICLE

The fact that some of the secondary particles produced in the decay of the τ^0-meson have a strong interaction with the nucleon and its mass value lies somewhere between 150 m_e and 350 m_e suggests that the τ^0-meson might be a composite particle. It might be, for example, made of one π^+- and one π^--meson, or of one proton and one τ^--meson. These pictures have, however, the common difficulty in explaining the τ^0-meson's mean lifetime of the order 10^{-10} sec. To illustrate the difficulty, it is useful to examine the picture that the τ^0-meson is a composite particle of one π^+- and one π^--meson bound together in some metastable state.

If the τ^0-meson is made of two π-mesons, its mass would be about 250 m_e larger than the sum of those of the two π-mesons. During the decay process, which is now to be pictured as similar to the α-decay rather than the β-decay, about 125 m_e of kinetic energy is imparted to each of the two charged π-mesons. To prevent two particles of such high energy to separate instantaneously, it must be assumed that a potential barrier of very great height and breadth exists between two charged π-mesons. Assuming a rectangular barrier of the height V and of the breadth b, the mean lifetime of the τ^0-meson should be of the order

$$\tau_{\tau^0} \cong \frac{r}{v} \exp\left\{\frac{2b}{\hbar c}\sqrt{2m_\pi(V-E)}\right\}, \tag{1}$$

where E is the kinetic energy of the escaping charged π-meson,

m_π the mass of the charged π-meson.

r the radius of the inside of the barrier,

v the velocity of the emitted charged π-meson.

Putting $m_\pi=276\,m_e$ r equal to the Compton wave length of the charged π-meson and $\tau_{\tau^0}=3\times10^{-10}$ sec., we have

$$\frac{b}{\hbar c}\sqrt{m_\pi(V-E)}=11.1. \tag{2}$$

Even if the barrier has a height of 200 Mev., the breadth of the barrier would be ten times the range of the nuclear force, which is an impossible assumption. It means that the interaction between two charged π-mesons not only is very strong, but also has a range very much larger than that of the nuclear force. The scattering of mesons by mesons would have then a very large cross-section. Consider the collision of two fast nucleons. Each fast moving nucleon with its meson field can be pictured as a group of fast moving virtual mesons coupled together with a bare nucleon. Owing to the big cross-section of the scattering of mesons by mesons, we would expect a cross-section for the nucleon scattering far larger than that given by the experiments.

In order that the range of the interaction between two charged π-mesons is of the order of that of the nuclear force, the height of the potential barrier have to be of the order of 10^4 Mev., which is about a hundred times the rest energy of the charged π-meson. Under such colossal interaction, particles are likely to be created and anhihilated continuously and it is doubtful whether there is any sense in treating the composite particle as two bound charged π-mesons only. Fermi and Yang[6] have suggested that all mesons are composite particles made of nucleons and anti-nucleons. In order to explain the observed value of the mass of the π-meson, they have to assume an interaction between two nucleous of a depth of 2.46×10^4 Mev. and a width of the order of the Compton wave length of the nucleon. Their theory is at present only a program and is unlikely to yield definite quantitative results in the near future. It is therefore premature to discuss the decay of the τ^0-meson in the light of this theory at this stage. Similar difficulty exists for other pictures treating the τ^0-meson as a composite particle.

6. E. Fermi and C. N. Yang, *Phys. Rev.* **76** (1949), 1739.

3. THE τ^o-MESON AS AN ELEMENTARY PARTICLE OF SPIN ZERO.

The decay of the π^o-meson into two photons with a half lifetime of 3×10^{-14} sec. gives strong support to the view that it is a particle of spin zero, as the decay of a particle with spin $\hbar$ into two photons is forbidden. Using the method of regularization, Steinberger[7] has calculated the mean lifetime of various kinds of mesons. In particular, the expressions for the mean lifetime τ of the neutral scalar and pseudo-scalar mesons for decaying into two photons are as follows:

a) Scalar meson with scalar coupling.

$$\tau\,(S.\ S.) = 18 \cdot \frac{(2\pi\hbar c)^3}{g^2 e^4} \cdot \left(\frac{M}{\mu}\right)^2 \cdot \frac{\hbar}{\mu}\,. \tag{3}$$

b) Scalar meson with vector coupling, Decay into two photons forbidden.

c) Pseudoscalar meson with pseudoscalar coupling,

$$\tau\,(PS.\ PS.) = 8 \cdot \frac{(2\pi\hbar c)^3}{g^2 e^4} \cdot \left(\frac{M}{\mu}\right)^2 \cdot \frac{\hbar}{\mu}\,. \tag{4}$$

d) Pseudoscalar meson with pseudo-vector coupling,

$$\tau\,(PS.\ PV.) = 72 \cdot \frac{(2\pi\hbar c)^3}{f^2 e^4} \cdot \left(\frac{M}{\mu}\right)^4 \cdot \frac{\hbar}{\mu}\,. \tag{5}$$

where g, f are the coupling constants between the nucleon and the neutral meson, M the rest mass of the nucleon, μ the rest mass of the neutral meson, e the electronic charge.

Putting μ equal to the mass of the π^o-meson, we have the following expressions for the mean lifetime of the π^o-meson for various kinds of coupling.

$$\begin{aligned} \tau_{\pi^o}\,(S.\ S.) &= 2 \times 10^{-14} \cdot \hbar c \,/\, g^2_{\pi^o} \text{ sec.} \\ \tau_{\pi^o}\,(PS.\ PS.) &= 0.9 \times 10^{-14} \cdot \hbar c \,/\, g^2_{\pi^o} \text{ sec.} \\ \tau_{\pi^o}\,(PS.\ PV.) &= 4 \times 10^{-12} \cdot \hbar c \,/\, f^2_{\pi^o} \text{ sec.} \end{aligned} \tag{6}$$

7. J. Steinberger, *Phys. Rev.* **76** (1949), 1180.

As $\hbar c/g_{\pi^0}^2$ and $\hbar c/f_{\pi^0}^2$ are of the order of one, the result agrees very well with the experiment, if it were assumed that the π^0-meson is a scalar particle with both scalar and vector couplings or a pseudoscalar particle with both pseudoscalar and pseudovector couplings.

Since the τ^0-meson decays into charged particles with a mean lifetime of 3×10^{-10} sec. instead of decaying into two photons, the mean lifetime of the τ^0-meson for decaying into two photons must be larger than 3×10^{-10} sec. Denoting the mean lifetimes of the τ^0-meson and π^0-meson for decaying into photons by τ_{τ^0} and τ_{π^0} respectively, we have then:

$$\frac{\tau_{\tau^0}}{\tau_{\pi^0}} > 10^4 \qquad (7)$$

Assuming that the mass of the τ^0-meson is three times of that of the π^0-meson, we have the following table for the ratio $\tau_{\tau^0}/\tau_{\pi^0}$ for various kinds of couplings.

TABLE. *The ratio $\tau_{\tau^0}/\tau_{\pi^0}$ for various kinds of couplings*

Coupling scheme for the τ^0-meson / Coupling scheme for the π^0-meson	Scalar meson Scalar coupling	Pseudoscalar meson Pseudoscalar coupling	Pseudoscalar meson Pseudovector coupling
Scalar meson Scalar coupling	$3.7 \times 10^{-2} \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$1.6 \times 10^{-2} \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$8.1 \times 10^{-1} \left(\frac{g_{\pi^0}}{f_{\tau^0}}\right)^2$
Pseudoscalar meson Pseudoscalar coupling	$8.3 \times 10^{-2} \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$3.7 \times 10^{-2} \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2$	$1.8 \left(\frac{g_{\pi^0}}{f_{\tau^0}}\right)^2$
Pseudoscalar meson Pseudovector coupling	$1.9 \times 10^{-4} \left(\frac{f_{\pi^0}}{g_{\tau^0}}\right)^2$	$8.4 \times 10^{-5} \left(\frac{f_{\pi^0}}{g_{\tau^0}}\right)^2$	$4.1 \times 10^{-3} \left(\frac{f_{\pi^0}}{f_{\tau^0}}\right)^2$

The suffix τ^0 or π^0 is used to distinguish the corresponding quantities belonging to a τ^0- or π^0-meson. It follows therefore:

$$\left(\frac{g_{\pi^o}}{g_{\tau^o}}\right)^2, \left[\text{or} \left(\frac{g_{\pi^o}}{f_{\tau^o}}\right)^2, \left(\frac{f_{\pi^o}}{g_{\tau^o}}\right)^2, \left(\frac{f_{\pi^o}}{f_{\tau^o}}\right)^2\right] \geqq 10^4 \tag{8}$$

It is difficult to reconcile the ratio between the numbers of π^o- and τ^o-mesons found in the penetrating shower and this ratio between the coupling constants. According to Anderson and his co-workers, the number of τ^o-meson created in the penetrating shower is about 3% of that of the ionizing particles produced. As not all of the ionizing particles in the penetrating shower are charged π-mesons, the upper limit of the ratio between the numbers of charged π-mesons and τ^o-mesons produced is $\cong 30$. Assuming that equal numbers of π^o- and charged π-mesons are produced, the ratio between the numbers of π^o- and τ^o-mesons produced is then

$$\frac{N_{\pi^o}}{N_{\tau^o}} \leqq 30 \tag{9}$$

On the other hand, this ratio is expected to be roughly $N_{\pi^o}/N_{\tau^o} \cong (g_{\pi^o}/g_{\tau^o})^2 > 10^4$ as a first approximation.

It is difficult to have a reliable estimation of the meson production cross-section during a nuclear collision. There exists yet no method with which one can treat the radiation reaction in the meson theory satisfactorily. It is not even known, how many kinds of mesons are strongly coupled with the nucleon and give substantial contributions to the interaction potential between two nucleons. However, it is still useful to discuss roughly the various factors influencing the production of mesons during a nuclear collision.

The production of the neutral meson in a nuclear collsion is a process similar to the Bremsstrahlung during the collision of an electron with a Coulomb field. To the first approximation, the matrix element can be regarded as consisting of two factors corresponding to the following two steps:

a) The emission of a neutral meson by a nucleon,

b) The transfer of the momentum between two colliding nucleons through their mutual nuclear potential U.

The first factor is proportional to the coupling constant g_{π^o} or g_{τ^o}. The second factor, which depends on the Fourier components, of U, should be roughly the same whether a π^o- or a τ^o-meson is produced, if the momenta transferred are the same. Disregarding the dependence of the matrix element on the energy of the colliding nucleons, the ratio N_{π^o}/N_{τ^o} in the penetrating shower is expected to be equal to $(g_{\pi^o}/g_{\tau^o})^2$ approximately.

However, as the mass of the τ^o-meson is three times as heavy as that of the π^o-meson, the momentum space available for the production of the

π^0-meson is larger than that of τ^0-meson. Besides, the spectrum of the incoming nucleon is proportional to $E^{-2.5}$, where E is the energy of the incoming nucleon. The number of nucleons decreases rapidly with increasing energy. There is a region at the lower end of the energy spectrum of the incoming nucleon, which, though available for the production of the π^0-meson, has not enough energy to produce τ^0-meson. Finally, as $g_{\pi^0}^2/\hbar c$ is of the order of unity, the multiple production of π^0-meson might make a substantial or even predominant contribution in comparison with that by the process of single production. On the other hand, if $g_{\tau^0}^2/\hbar c$ is as small as indicated by (8), the higher order contribution to the production of the τ^0-meson must be negligible. All these factors favor the production of π^0-meson and thus make

$$\frac{N_{\pi^0}}{N_{\tau^0}} > \left(\frac{g_{\pi^0}}{g_{\tau^0}}\right)^2. \tag{10}$$

On the other hand, it is quite possible, that due to the different coupling schemes for the π^0- and τ^0-meson, the cross-section for the production of τ^0-meson relative to that of the π^0-meson increases with the energy of the colliding nucleons. However, as the number of the incoming nucleons decreases with the energy, this effect can hardly be predominant.

It is therefore difficult to reconcile the formulae (8), (9) and (10). If g_{τ^0} were as small as indicated by (8), the number of τ^0-mesons in the penetrating shower should be very much smaller than that actually observed. The only possible explanation is that the τ^0-meson is not directly produced in a nuclear collision. Being not directly coupled with the nucleon, it has only a small probability of decaying into two photons through the creation of a virtual pair of nucleon and anti-nucleon. It follows therefore, that if the spin of the τ^0-meson is zero, it is a secondary decay product of some still heavier particle produced directly in a nuclear collision.

4. THE τ^0-MESON AS AN ELEMENTARY PARTICLE OF SPIN $\hbar$

On account of the conservation of angular momentum, it is impossible for a vector or pseudovector meson to decay into two photons. According to Steinberger, even the decay of a pseudovector meson into three photons is also forbidden. For the decay of a vector meson into three photons, the transition probability is proportional to e^6 and therefore smaller than that for the decay of a scalar or pseudoscalar meson into two photons, which is proportional to e^4. The expression for the mean lifetime of a neutral vector meson with vector coupling decaying into three photons is given by Steinberger as:

$$\tau\,(V.\,V.) \cong 200 \cdot \frac{(2\,\pi\,\hbar\,c)^4}{g^2\,e^6} \cdot \left(\frac{M}{\mu}\right)^8 \cdot \frac{\hbar}{\mu}\,, \tag{11}$$

while that for a neutral vector meson with tensor coupling is of the same order of magnitude. The ratio between the mean lifetime of a vector τ^o-meson and that of a pseudoscalar π^o-meson with, let us say, pseudoscalar coupling is

$$\frac{\tau_{\tau^o}}{\tau_{\pi^o}} \cong 25 \cdot \frac{2\,\pi\,\hbar\,c}{e^2} \cdot \left(\frac{g_{\pi^o}}{g_{\tau^o}}\right)^2 \cdot \frac{\mu_{\pi^o}^3\,M^6}{\mu_{\tau^o}^9} = 1.3 \times 10^5 \left(\frac{g_{\pi^o}}{g_{\tau^o}}\right)^2, \tag{12}$$

which, according to (7), should be larger than 10^4. The value of $(g_{\pi^o}/g_{\tau^o})^2$ derived therefrom is consistent with (10). It follows therefore, that if the τ^o-meson is produced directly in a nuclear collision, it might have a spin $\hbar$.