DETERMINATION OF THE TWO-PHOTON DECAY RATE OF THE η MESON*

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The recent experiment of Chrétien et al.[1] demonstrates directly the existence of a two-photon decay mode of the η meson and establishes firmly the quantum number assignment $J(\eta)=0$, $P(\eta)=-1$, $C(\eta)=1$.[2] Since the corresponding π^0-meson quantum number assignment is $J(\pi^0)=0$, $P(\pi^0)=-1$, $C(\pi^0)=1$, the photon decay modes of the (isoscalar, $G=+1$) η may be treated in an entirely similar manner to those of the (isovector, $G=-1$) π^0. In particular, we suggest that the two-photon decay rate of the η, $\Gamma_{\eta\to\gamma+\gamma}$, be determined by measuring the Coulomb field contribution to the differential cross section for η photoproduction on a high-Z nucleus, $\{[d\sigma/d\Omega]_C\}_\eta$; an analogous determination of $\Gamma_{\pi^0\to\gamma+\gamma}$ from a measurement of $\{[d\sigma/d\Omega]_C\}_{\pi^0}$ has already been reported.[3] Any such determination of $\Gamma_{\eta\to\gamma+\gamma}$ will immediately yield the η lifetime, τ_η, since already available evidence indicates that[4]

$$\Gamma_{\eta\to\gamma+\gamma}/(\tau_\eta)^{-1} \cong \Gamma_{\eta\to\gamma+\gamma}/(\Gamma_{\eta\to\gamma+\gamma} + \Gamma_{\eta\to\pi^0+\pi^0+\pi^0} + \Gamma_{\eta\to\pi^+ + \pi^- + \pi^0}) \cong 0.4.$$

Using the theory of π^0 photoproduction in the Coulomb field of a high-Z nucleus of mass M,[5] the differential cross section for η photoproduction, $\{d\sigma/d\Omega\}_\eta$, may be written as

$$\{d\sigma/d\Omega\}_\eta = |\{A_C\}_\eta + \{A_{\text{strong}}\}_\eta|^2,$$

$$\{[d\sigma/d\Omega]_C\}_\eta \equiv |\{A_C\}_\eta|^2 = (8e^2/4\pi)(\Gamma_{\eta\to\gamma+\gamma}/m_\eta^3)(p_\eta^4 \sin^2\theta_\eta/\beta_\eta q_\eta^4)|ZF_C(q_\eta^2)|^2,$$

$$\{[d\sigma/d\Omega]_{\text{strong}}\}_\eta \equiv |\{A_{\text{strong}}\}_\eta|^2 = (\sigma_\eta \sin^2\theta_\eta)|AF_{\text{strong}}(q_\eta^2)|^2; \tag{1}$$

$$\sigma_\eta \equiv |(Z/A)\{\alpha_p\}_\eta + [(A-Z)/A]\{\alpha_n\}_\eta|^2,$$

$$\beta_\eta = p_\eta/(p_\eta^2+m_\eta^2)^{1/2} \cong 1 - m_\eta^2/2p_\eta^2, \quad p_\gamma = (p_\eta^2+m_\eta^2)^{1/2} \ll M,$$

$$q_\eta \equiv |\vec{p}_\gamma - \vec{p}_\eta| = p_\eta\beta_\eta^{-1/2}[(\beta_\eta^{-1/2}-\beta_\eta^{1/2})^2 + 4\sin^2(\theta_\eta/2)]^{1/2} \cong p_\eta[(m_\eta^2/2p_\eta^2)^2+\theta_\eta^2]^{1/2};$$

where $\{A_C\}_\eta$ and $\{A_{\text{strong}}\}_\eta$ are the Coulomb field and the strong-interaction contributions to the amplitude for η photoproduction, i.e., the contributions arising, respectively, from the exchange of a virtual longitudinal photon and, say, the exchange of a virtual ω meson; it should be noted that we neglect any η reabsorption corrections in the above expression for $\{A_{\text{strong}}\}_\eta$. Further, β_η and p_η are the velocity and the momentum of the outgoing η meson; p_γ is the momentum of the incoming photon; θ_η is the angle between p_η and p_γ; $F_C(q_\eta^2)$ and $F_{\text{strong}}(q_\eta^2)$ are form factors of the (assumed spin-zero) target nucleus at momentum transfer q_η [$F_{\text{strong}}(q_\eta^2) \cong F_C(q_\eta^2) = F_{\text{electric scattering}}(q_\eta^2)$]; and $\{\alpha_p\}_\eta \times \sin\theta_\eta$ and $\{\alpha_n\}_\eta \sin\theta_\eta$ are (within the context of the usual impulse approximation for a spin-zero nucleus) the strong-interaction-contributed non-spin-flip amplitudes for η photoproduction on a proton and neutron, respectively.[6] It should be noted that we neglect the incoherent (target-nucleus exciting) portion of $\{A_{\rm strong}\}_\eta$ because of its rather effective suppression at small q_η by the exclusion principle[7]; in a similar way we neglect the incoherent portion of $\{A_{\rm C}\}_\eta$.

We now attempt to give an a priori estimate of the quantity R_η, where [see Eq. (1)]

$$R_\eta^{\,2} \equiv \frac{\{[d\sigma/d\Omega]_{\rm C}\}_\eta}{\{[d\sigma/d\Omega]_{\rm strong}\}_\eta},$$

$$\cong \left(\frac{Z}{A}\right)^2 \left(8\frac{e^2}{4\pi}\right)\left(\frac{\Gamma_{\eta\to\gamma+\gamma}/m_\eta^{\,3}}{\sigma_\eta}\right)\left(\frac{p_\eta^{\,4}}{\beta_\eta q_\eta^{\,4}}\right),$$

$$\cong \left(\frac{Z}{A}\right)^2 \left(8\frac{e^2}{4\pi}\right)\left(\frac{\Gamma_{\eta\to\gamma+\gamma}/m_\eta^{\,3}}{\sigma_\eta}\right)\Bigg/\left[\left(\frac{m_\eta^{\,2}}{2p_\eta^{\,2}}\right)^2+\theta_\eta^{\,2}\right]^2. \tag{2}$$

The numerical magnitude of R_η $(= |\{A_{\rm C}\}_\eta|^2/|\{A_{\rm C}\}_\eta|\cdot|\{A_{\rm strong}\}_\eta|)$ is decisive in any evaluation of the possibility of a successful determination of $\Gamma_{\eta\to\gamma+\gamma}$ from a measurement of $\{d\sigma/d\Omega\}_\eta$ as a function of Z, θ_η, and p_γ. In particular, the quantity R_η is to be compared with the corresponding quantity R_{π^0}, where

$$R_{\pi^0}^{\,2} \equiv \frac{\{[d\sigma/d\Omega]_{\rm C}\}_{\pi^0}}{\{[d\sigma/d\Omega]_{\rm strong}\}_{\pi^0}},$$

$$\cong \left(\frac{Z}{A}\right)^2 \left(8\frac{e^2}{4\pi}\right)\left(\frac{\Gamma_{\pi^0\to\gamma+\gamma}/m_\pi^{\,3}}{\sigma_{\pi^0}}\right)\left(\frac{p_\pi^{\,4}}{\beta_\pi q_\pi^{\,4}}\right),$$

$$\cong \left(\frac{Z}{A}\right)^2 \left(8\frac{e^2}{4\pi}\right)\left(\frac{\Gamma_{\pi^0\to\gamma+\gamma}/m_\pi^{\,3}}{\sigma_{\pi^0}}\right)\Bigg/\left[\left(\frac{m_\pi^{\,2}}{2p_\pi^{\,2}}\right)^2+\theta_\pi^{\,2}\right]^2,$$

$$\approx 5\times10^{-7}\Bigg/\left[\left(\frac{m_\pi^{\,2}}{2p_\pi^{\,2}}\right)^2+\theta_\pi^{\,2}\right]^2 = 20; \tag{3}$$

and where we have taken[3] $\theta_\pi = m_\pi^{\,2}/2p_\pi^{\,2}$, $p_\pi = 1$ BeV/c, $Z = 82$, and $A = 208$, and also used the empirically known values of[8] $\Gamma_{\pi^0\to\gamma+\gamma}$ ($\cong 5\times10^{15}$ sec^{-1}) and[9] σ_{π^0} ($\approx 10^{-29}$ cm^2/sr at $p_\pi = 1$ BeV/c). Assuming that $\pi^0\to\gamma+\gamma$ and $\eta\to\gamma+\gamma$ proceed predominantly via $\pi^0\to\rho^0+\omega$ followed by $\rho^0\to\gamma$, $\omega\to\gamma$, and $\eta\to\rho^0+\rho^0$ or $\eta\to\omega+\omega$ followed by $\rho^0\to\gamma$ and $\rho^0\to\gamma$ or $\omega\to\gamma$ and $\omega\to\gamma$,[10] we have

$$\frac{\Gamma_{\eta\to\gamma+\gamma}/m_\eta^{\,3}}{\Gamma_{\pi^0\to\gamma+\gamma}/m_\pi^{\,3}} \approx \frac{g_{\eta\omega\omega}^{\,2}/4\pi}{g_{\pi\rho\omega}^{\,2}/4\pi}, \tag{4}$$

where the g's are coupling constants characterizing the indicated vertices and where we have in addition assumed that $g_{\eta\omega\omega}\approx g_{\eta\rho\rho}$ and $g_{\rho\gamma}\approx g_{\omega\gamma}$.

Equations (2)-(4) then yield

$$\frac{R_\eta^{\,2}}{R_{\pi^0}^{\,2}} \approx \left(\frac{g_{\eta\omega\omega}^{\,2}/4\pi}{g_{\pi\rho\omega}^{\,2}/4\pi}\right)\cdot\left(\frac{\sigma_{\pi^0}}{\sigma_\eta}\right)\cdot\frac{(p_\eta/q_\eta)^4}{(p_\pi/q_\pi)^4}$$

$$\cong \left(\frac{g_{\eta\omega\omega}^{\,2}/4\pi}{g_{\pi\rho\omega}^{\,2}/4\pi}\right)\cdot\left(\frac{\sigma_{\pi^0}}{\sigma_\eta}\right)\cdot\frac{[(m_\pi^{\,2}/2p_\pi^{\,2})^2+\theta_\pi^{\,2}]^2}{[(m_\eta^{\,2}/2p_\eta^{\,2})^2+\theta_\eta^{\,2}]^2}, \tag{5}$$

and, since it is plausible to assume also that $(g_{\eta\omega\omega}^{\,2}/4\pi)\approx(g_{\pi\rho\omega}^{\,2}/4\pi)$,[11] we see that the value of R_η/R_{π^0} is, essentially, equal to the value of $[(\sigma_{\pi^0}/\sigma_\eta)(p_\eta/q_\eta)^4/(p_\pi/q_\pi)^4]^{1/2}$.

We now consider two more or less extreme possibilities. Suppose first that σ_{π^0} and σ_η vary relatively slowly with p_π and p_η in the range of, say, $1\ \mathrm{BeV}/c \lesssim (p_\pi, p_\eta) \lesssim 5\ \mathrm{BeV}/c$, and that in this range the ratio of $\sigma_{\pi^0}/\sigma_\eta$ is of order unity[12]—this assumption is not unreasonable if $\gamma + N \to (\pi, \eta) + N$ proceed predominantly via one-nucleon intermediate states and if $(g_{NN\pi}^2/4\pi) \approx (g_{NN\eta}^2/4\pi)$. Under these circumstances, Eq. (5) shows that, for $\theta_\eta = \theta_\pi$, the ratio R_η/R_{π^0} is of the order unity if $p_\eta/p_\pi = m_\eta/m_\pi$, i.e., if the ratio of the incoming photon momenta in the corresponding η and π^0 photoproduction experiments is equal to $m_\eta/m_\pi = 4$—say 4 BeV and 1 BeV to yield $R_\eta \approx R_{\pi^0} \approx (20)^{1/2} = 4.5$ [Eq. (3)]. Conversely, suppose that with $(p_\eta, p_\pi) \gtrsim 1\ \mathrm{BeV}/c$, the amplitudes $\{A_{\mathrm{strong}}\}_\eta$ and $\{A_{\mathrm{strong}}\}_{\pi^0}$ are dominated at small θ_η and θ_π by the exchange of a virtual ω meson[13]; then, remembering that an ω meson and a photon have the same quantum numbers except for mass and comparing the expressions in Eq. (1) for $\{A_C\}_{\eta,\pi^0}$ and $\{A_{\mathrm{strong}}\}_{\eta,\pi^0}$, we obtain

$$\sigma_\eta \approx \tfrac{3}{2}(8g_{NN\omega}^2/4\pi)(\Gamma_{\omega\to\gamma+\eta}/M_\eta^3)[p_\eta^4/\beta_\eta(q_\eta^2+m_\omega^2)^2],$$

$$\sigma_{\pi^0} \approx \tfrac{3}{2}(8g_{NN\omega}^2/4\pi)(\Gamma_{\omega\to\gamma+\pi^0}/M_\pi^3)[p_\pi^4/\beta_\pi(q_\pi^2+m_\omega^2)^2],$$

$$M_\eta \equiv m_\omega - m_\eta^2/m_\omega,\quad M_\pi \equiv m_\omega - m_\pi^2/m_\omega,$$

$$q_\eta^2 \ll m_\omega^2,\quad q_\pi^2 \ll m_\omega^2; \tag{6}$$

whence it is seen that σ_η and σ_π^0 increase with p_η and p_π as p_η^4 and p_π^4. In addition, the dominant mechanism assumed above for $\pi^0 \to \gamma+\gamma$ and $\eta \to \gamma+\gamma$ implies that $\omega \to \gamma+\pi^0$ and $\omega \to \gamma+\eta$ proceed predominantly via $\omega \to \rho^0 + \pi^0$, followed by $\rho^0 \to \gamma$, and $\omega \to \omega + \eta$, followed by $\omega \to \gamma$, so that[10]

$$\frac{\Gamma_{\omega\to\gamma+\pi^0}/M_\pi^3}{\Gamma_{\pi^0\to\gamma+\gamma}/m_\pi^3} \approx \frac{\Gamma_{\omega\to\gamma+\eta}/M_\eta^3}{\Gamma_{\eta\to\gamma+\gamma}/m_\eta^3} \approx \frac{1}{2\pi}\left(\frac{q_{\omega\gamma}^2}{4\pi}\right)^{-1} \equiv 2\left(\frac{e^2/4\pi}{\gamma_\omega^2/4\pi}\right)^{-1}. \tag{7}$$

Equations (2), (3), (6), and (7) yield

$$R_\eta^2 \approx Km_\omega^4/q_\eta^4 \cong \frac{Km_\omega^4}{p_\eta^4[(m_\eta^2/2p_\eta^2)^2+\theta_\eta^2]^2},$$

$$R_{\pi^0}^2 \approx Km_\omega^4/q_\pi^4 \cong \frac{Km_\omega^4}{p_\pi^4[(m_\pi^2/2p_\pi^2)^2+\theta_\pi^2]^2},$$

$$K \equiv [(Z/A)^2\tfrac{1}{3}(e^2/4\pi)^2/(g_{NN\omega}^2/4\pi)(\gamma_\omega^2/4\pi)]$$
$$\approx 5\times10^{-7}(1\ \mathrm{BeV}/m_\omega)^4 = 1.3\times10^{-6}; \tag{8}$$

so that for $\theta_\eta = m_\eta^2/2p_\eta^2$, $\theta_\pi = m_\pi^2/2p_\pi^2$,

$$R_\eta^2 \approx 5\times10^{-6}(m_\omega p_\eta/m_\eta^2)^4,$$
$$R_{\pi^0}^2 \approx 5\times10^{-6}(m_\omega p_\pi/m_\pi^2)^4. \tag{9}$$

Equation (9) shows that the ratio R_η/R_{π^0} is of the order unity if $p_\eta/p_\pi = m_\eta^2/m_\pi^2$, i.e., if the ratio of the incoming photon momenta in the corresponding η and π^0 photoproduction experiments is equal to $m_\eta^2/m_\pi^2 = 16$; as a numerical example, $R_\eta \approx 4.5$ for an incoming photon energy of 16 BeV ($\theta_\eta = m_\eta^2/2p_\eta^2 = 0.6$ mrad) and $R_\eta \approx 0.6$ for an incoming photon energy of 6 BeV ($\theta_\eta = m_\eta^2/2p_\eta^2 = 4$ mrad). It is therefore clear that any actual rapid increase of σ_η with p_η will necessitate the use of rather high incoming photon energies for the successful determination of $\Gamma_{\eta\to\gamma+\gamma}$ from a measurement of $\{d\sigma/d\Omega\}_\eta$ as a function of Z, θ_η, and p_γ.[14]

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[11]This assumption, together with Eq. (4) and the empirically known value of $\Gamma_{\pi^0\to\gamma+\gamma}$ given in reference 8, yields

$$\Gamma_{\eta\to\gamma+\gamma} \approx (m_\eta^3/m_\pi^3)\Gamma_{\pi^0\to\gamma+\gamma} \cong 3\times 10^{17}\ \mathrm{sec}^{-1};$$

$$\tau_\eta \cong 0.4(\Gamma_{\eta\to\gamma+\gamma})^{-1} \approx 10^{-18}\ \mathrm{sec}.$$

[12]A recent experimental limit on η photoproduction in hydrogen indicates that $\sigma_{\pi^0}/\sigma_\eta > 2$ for $p_\eta \approx p_\pi \approx 1$ BeV/c. See A. Silverman, K. Berkelman, A. Franklin, D. McLeod, and S. Richert, presented by A. Silverman at the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published).

[13]Evidence for this in the π^0 case is presented in reference 9 and in the work of H. Ruderman, R. Gomez, R. M. Talman, and A. V. Tollestrup (to be published) very briefly described in this reference.

[14]A very crude consideration of the exchange of a "Reggeized" rather than an "un-Reggeized" virtual ω meson and of a "Reggeized" rather than an "un-Reggeized" virtual longitudinal photon leads to values of R_η and R_{π^0} which differ from the values given in Eqs. (8) and (9) by factors

$$\approx (Z_\eta)^{\{[\alpha_\gamma(-q_\eta^2)-1]-[\alpha_\omega(-q_\eta^2)-1]\}}$$

and

$$\approx (Z_\pi)^{\{[\alpha_\gamma(-q_\pi^2)-1]-[\alpha_\omega(-q_\pi^2)-1]\}}$$

$$(\text{for } Z_{\eta,\pi} \gg 1).$$

Here $Z_{\eta,\pi}$, the cosine of the scattering angle in the crossed channel, is given by

$$Z_{\eta,\pi} = 2[2Mp_\gamma - \tfrac{1}{2}(q_{\eta,\pi}^2 + m_{\eta,\pi}^2)]/[(4M^2 + q_{\eta,\pi}^2) \times (q_{\eta,\pi} + m_{\eta,\pi}^2/q_{\eta,\pi})^2]^{1/2},$$

$$\cong 2p_\gamma q_{\eta,\pi}/(q_{\eta,\pi}^2 + m_{\eta,\pi}^2),$$

while $\alpha_\omega(-q_{\eta,\pi}^2)$ and $\alpha_\gamma(-q_{\eta,\pi}^2)$ describe the Regge-pole trajectories of the ω meson and of the longitudinal photon [$\alpha_\omega(m_\omega^2) = 1$, $\alpha_\gamma(0) = 1$, $\alpha_\omega(-q_{\eta,\pi}^2) \approx 1 - (q_{\eta,\pi}^2 + m_\omega^2)/(50\, m_\pi^2)$ for $q_{\eta,\pi}^2 \lesssim \frac{1}{4} m_{\eta,\pi}^2$, $\alpha_\gamma(-q_{\eta,\pi}^2) \approx 1$ for

$q_{\eta,\pi}{}^2 \lesssim \frac{1}{4}m_{\eta,\pi}{}^2$—for a general discussion of Regge-poles see the report of S. D. Drell on high-energy theory presented at the International Conference on High-Energy Nuclear Physics, Geneva, 1962 (CERN, Geneva, Switzerland, to be published)]. The factors

$$(Z_\eta)^{[\alpha_\gamma(-q_\eta^2)-\alpha_\omega(-q_\eta^2)]}$$

and

$$(Z_\pi)^{[\alpha_\gamma(-q_\pi^2)-\alpha_\omega(-q_\pi^2)]}$$

are each only a little greater than unity if we take $\theta_\eta \approx m_\eta^2/2p_\eta^2$ and $\theta_\pi \approx m_\pi^2/2p_\pi^2$, i.e., take $q_\eta \approx \sqrt{2}\,m_\eta^2/2p_\eta$ and $q_\pi \approx \sqrt{2}\,m_\pi^2/2p_\pi$; thus we believe that Regge-type corrections to Eqs. (8) and (9) are relatively small in just that range of q_η and q_π where R_η and R_{π^0} are largest. On the other hand, for $\theta_\eta \approx m_\eta/2p_\eta$ and $\theta_\pi \approx m_\pi/2p_\pi$, i.e., for $q_\eta \approx \frac{1}{2}m_\eta$ and $q_\pi \approx \frac{1}{2}m_\pi$, we have

$$(Z_\eta)^{[\alpha_\gamma(-q_\eta^2)-\alpha_\omega(-q_\eta^2)]} \approx (p_\gamma/m_\eta)^{0.7}$$

and

$$(Z_\pi)^{[\alpha_\gamma(-q_\pi^2)-\alpha_\omega(-q_\pi^2)]} \approx (p_\gamma/m_\pi)^{0.6},$$

and these are each appreciably greater than unity for p_γ equal to, say, $10\,m_\eta$ (5.5 BeV/c) and $10\,m_\pi$ (1.4 BeV/c); however, we must remember that for $q_\eta \approx \frac{1}{2}m_\eta$, the form factors $F_C(q_\eta^2)$ and $F_{\rm strong}(q_\eta^2) \cong F_C(q_\eta^2)$ are becoming so small that the previously neglected incoherent portions of $\{[d\sigma/d\Omega]_C\}_\eta$ and particularly of $\{[d\sigma/d\Omega]_{\rm strong}\}_\eta$ are no longer umimportant.

NEGATIVE MUON POLARIZATION IN PHOSPHORUS AND FLUORINE*

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This Letter reports a measurement of the polarization of negative muons stopped in two substances of nuclear spin $\frac{1}{2}$, red phosphorus ($_{15}P^{31}$) and fluorine ($_9F^{19}$) in the form of lithium fluoride.

A polarized negative muon, stopping in a nuclear spin-$\frac{1}{2}$ target, cascades rapidly down to the 1s orbital state and then into one of the two hyperfine states, $F=0$ or $F=1$. Those muons that end in the $F=0$ state are effectively depolarized, whereas those in the $F=1$ state are not. A measurement of the negative muon polarization becomes essentially a measurement of the population of the $F=1$ state. Arguments have been advanced to show that Auger transitions from $F=1$ (the higher state) to $F=0$ should depopulate the $F=1$ state in phosporus in times short compared to the negative muon lifetime (~0.6 μsec), and therefore no polarization should be seen.[1] Experimental results have been obtained which support[1] and contradict[2] these arguments. Reference 2 gives a negative muon polarization which is one half the polarization in a spin-zero target. This number is what one expects from the initial mixture of $F=1$ and $F=0$ states with no transitions from $F=1$ to $F=0$.

In the case of fluorine, a time dependence, with a time constant of about a half microsecond, has been observed in the rate of nuclear muon capture, and attributed to transitions from $F=1$ to $F=0$, since these two states have different capture rates.[3]

To shed more light on this question of hyperfine transition, the polarization of negative muons in phosphorus and fluorine was investigated by precessing the negative muon spins in a relatively high field (2 kG) and looking for oscillations in the time distribution of decay electrons emitted in a fixed laboratory direction. The time distribution is obtained in a straightforward manner with an analog time-to-height converter feeding a conventional pulse-height analyzer. The experimental setup is shown in Fig. 1.

To test the system, a run was made using a sulfur (nuclear spin = 0) target in a field of 1.00 ± 0.05 kG. The negative muon precession frequency in this case is the free muon frequency within 5×10^{-3},[4] or about 13.5 Mc/sec. The lifetime is ~0.6 μsec. The time distribution for about 80 000 decay electrons is shown in Fig. 2. Since the precession frequency is barely visible here, the frequency spectrum of the data (with the exponential removed) was obtained by means of an IBM-7090 computer program and is shown in Fig. 3(a). The asymmetry thus obtained is 4.2% with an error of perhaps 0.5%. This asymmetry is consistent with other measurements on the same beam.